THE ORIGIN OF THE ROCKS OF ACH'UAINE AND APPINITE TYPES in the ROGART AREA, SUTHERLAND.

(A Petrological and Geochemical Study of Granitisation Phenomena in the Rogart District, Sutherland.)

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THESIS SUBMITTED TO THE UNIVERSITY OF EDINBURGH FOR THE DEGREE OF DOCTOR OF PHILOSOPHY, 1948.

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I. INTRODUCTION

As long ago as 1912 (pp. 128-9) the late Sir John Flett made reference to the occurrence in the Moine series of the Northern Highlands of Scotland of a peculiar suite of basic rocks in which high proportions of ferromagnesian minerals, including hornblende, biotite, pyroxene and olivine, are associated with alkali feldspars (orthoclase and sodic oligoclase) and quartz. In concluding his description of a particular member of the suite (connected with the scyelite of Carn Cas nan Gabhar), he directed attention to the abnormal character of the rock in the following words: "The rock is far from being a normal diorite; neither is it a syenite. The abundance of ferromagnesian minerals in a mesostasis rich in silica and alkalies is a feature which recalls the lamprophyres".

Read encountered a large number of these curious basic rock masses during his regional geological investigation of the Northern Highlands (1925, pp. 45-51; 1926, pp. 154-166; 1931, pp. 165-172) and he gave them the name Hybrid rocks of Ach'uaine Type after the district of Ach'uaine, 2½ miles north-north-east of Bonar Bridge, where they are typically developed. According to Read these rocks constitute a group of minor intrusions of widely varied composition ranging from ultrabasic to acid; he attributed the various members of the series to "the mixing of a granitic /

granitic magma either with an ultrabasic magma or with solid ultrabasic rock", (1925, p. 45; 1926, p. 155). He dated the "hybrid" rocks (i.e. the time of hybridisation of the earlier ultrabasic intrusions by the later granitic intrusions) as later than the regional metamorphism of the Moines, but earlier than the deposition of the local Old Red Sandstone. The granite intrusions of the region are of two main types: (a) Migdale granite; (b) Lairg-Rogart granodiorite (1926, pp. 9 and 148). Later, after studying both the Loch Choire and Strath Halladale Complexes and the rocks of Ach'uaine Type associated with them, Read entertained the view that "The acid end of the series is possibly derived from the granitic injections of Loch Choire or Strath Halladale, so that these hybrids may be a special facies of injection-rocks". (Read, 1931, p. 165).

MacGregor and Kennedy (1932, pp. 105-119) drew attention to the close resemblance between the Lairg-Rogart granodiorite and its associated rocks of Ach'uaine Type and the Morven-Strontian 'Granites' and its associated Appinitic suite. They established the time-sequence as follows (p. 119):

(1) Regional injection of acid pegmatitic magma.

(2) Intrusion of ultrabasic to acid igneous rocks (Appinite-lamprophyre suite).

(3) Intrusion of Morvern-Strontian 'Granite' of Caledonian, probably Lower Old Red Sandstone, age.

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In his summary of the regional geology of the Northern Highlands, J. Phemister (1936, pp. 60-1), following MacGregor an Kennedy, grouped the rocks of Ach'uaine Type with the rocks of the Appinitic suite and dated them as members of the Newer Igneous Rocks of Caledonian age. Phemister also stressed the important facts that the rocks of Ach'uaine and Appinitic types are definitely associated, in their distribution, with the 'Newer Granite' stocks and that they appear to be absent from central and southern Ross-shire where the 'Newer Granites' are not represented.

In the course of the present investigation the writer has made a detailed study of the rocks of Ach'uaine and Appinitic types in the Rogart area. In addition to the masses of Ach'uai type recorded by Read (1925, pp. 45-51) from this area, he has mapped many more newly discovered occurrences of such rocks. Besides mapping the basic bodies on the six-inch scale, he has also made large-scale drawings of typical exposures. He has, moreover, visited the type localities of the so-called 'Hybrids' in the Ach'uaine region itself near Bonar Bridge under the guidance of Miss J. Watson, and has examined the rocks of the Bettyhill area, the "Hornblendic Complex" of which has already been described in great detail by Y.C. Cheng (1942, p. 67; 1944, p. 107).

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In a description of an agmatite formed from a hornblend -biotite-pyroxene-schist in the Rogart area, the writer (Ma, 1948, pp.8-14; and pp.153-9 of this thesis) has already shown that hornblendite developed as a basic front in the schist as a result of introduction and fixation of cafemic constituents displaced from parts of the rock body which were undergoing granitisation. The subsequent granitisation of the initially basified rocks gave rise to the series: hornblendite ⟶ appinitic rocks ⟶ dioritic migmatite ⟶ granodiorite. Some of these rock types resemble the 'Hybrids of Ach'uaine Type' so closely as to provide a clue towards the solution of the problem of the origin of this curious suite of rocks.

II. THE GEOLOGICAL SETTING OF THE ROGART AREA

The Rogart area considered in this thesis forms only a small portion of the extensive migmatite province which stretches across the Northern Highlands of Scotland right up to the north coast, and has an area of more than 700 square miles. The restricted region here described lies between Srath Càrnaig and Strath Brora, falling mainly within the parish of Rogart and partly in the parishes of Golspie and Dornarch, and having an area of about 37 square miles.

The Rogart area is not only an ideal region for the study of the petrological, mineralogical and chemical changes brought about during the migmatisation of the various Moine types, but it also provides excellent illustrations of the more advanced stages of the migmatisation processes which lead to large scale granitisation, these processes having culminated in this area with the development of granodiorite.

The area is divisible into three petrological zones: (1) A zone of veined Moine rocks; (2) a zone of migmatites; and (3) a zone of granodiorite. The Moine Series is represented in this area chiefly by siliceous and semi-pelitic granulites with quite subordinate bands of pelitic and semi-pelitic schists. In addition, there are basic rocks occurring (a) as large sheets of /

of hornblendic rocks round Creag Dail na Maine; these resemble the hornblendic rocks of Durcha Type (Read, 1925, pp. 18-20; 1926, pp. 144-7) which were considered by Read to represent metamorphosed lime- and magnesia-bearing sediments; and (b) as small hornblendic masses considered by Read to represent basic dykes and sills that were intruded into the Moines prior to the period of regional metamorphism.

All the pre-existing country rocks have suffered a profound alteration in the migmatite zone, and because the migmatisation was generally not completed at the crustal level now exposed, every stage of transition from unaltered Moine rocks to striped migmatites and granodiorite can be traced along the strike. An increasing degree of migmatisation is found, moreover, in a traverse from the outer margin of the zone of migmatites inwards toward the granodiorite. The contacts between the Moine rocks and the zone of migmatites, and between the latter zone and the granodiorite are gradational; consequently the geological boundaries as drawn on the map of the Geological Survey Sheet 103 are necessarily somewhat arbitrary. In the zone of migmatites, and even within the granodiorite itself, the original structures of the pre-existing Moine rocks are still preserved in a spectacular manner, and the writer therefore thinks that the whole process of transformation /

transformation can only have taken place while the rocks themselves remained solid.

It should be noted here that the writer has found it necessary to discriminate between rocks of Ach'uaine type (as redefined on page 71) and rocks of the appinitic suite (using the term 'appinite' in its original sense, as defined by Bailey). Examples of both of these series of rocks have hitherto been grouped together under Read's term "Hybrids of Ach'uaine Type". Since the appinitic examples have well recognised characters of their own, and represent a later stage of petrogenetic evolution, it has seemed desirable to separate them from the original composite group of "Hybrids of Ach'uaine Type", leaving only the other members of this group to be referred to as rocks of Ach'uaine type.

In the course of this thesis, the writer sets out the evidence from which he infers that during the general migmatisation of the region the hornblendic rocks of the Moine Series were transformed first by a process of basification into rocks of Ach'uaine type (in the sense as limited above), and subsequently, as a result of granitisation, into appinitic varieties and locally into granodiorite. These findings settle the vexed question as to the age of the rocks of Ach'uaine type and the associated appinitic varieties. The initial solid framework /

framework of these rocks is older than the Moine foliation, whilst their present-day mineralogical dress is post-foliation and of the same age as the migmatisation. A full account will be given of the field occurrence of all the basic masses (the so-called Hybrids of Ach'uaine Type) in the Rogart area, and a systematic petrological study will be presented of those examples which retain evidence of their ancestry.

III. FIELD OBSERVATIONS

1. Hornblendic Rocks in the Moine Series.

(a) Hornblendic rocks of probable sedimentary origin

Hornblendic sheets which Read regards as of sedimentary origin occur interbedded with the Moine granulites to the south of the Rogart migmatite area (i) between Srath Càrnaig and Dróighneach, around the crags of Creag Dail na Méine and west of Ach' Torra' Dhamh; (ii) further south on Cnoc na Feadaige and Creag Laith, where they are represented by numerous thin bands; (iii) between Loch Laoigh and Loch Lànnaidh on the north side of the Evelix valley; and (iv) on Beinn Bhreac to the south of the Evelix valley. The rock types are essentially the same in all occurrences, but the following description concerns only the rocks of the first of these localities, one which is situated within the area that has been investigated in detail by the writer.

A sheet of hornblendic rock with a maximum width of about 115 yds, is well exposed on a crag west of Ach' Torra' Dhamh, about a quarter of a mile south of the summit of An Dróighneach. In its middle part it consists of well foliated hornblende-schist and amphibolite, with narrow lamellae and patches of quartzo-feldspathic materials, and hornblende prisms of /

of about 2 x 1 mm. in size. The foliation of the hornblende-schist is so perfect that the rock can be split into thin slabs, commonly with a flat surface. A very faint development of the 'b' axis (Sander) was observed in the hornblende-schist toward the north-eastern end of the section where the plane foliation strikes N.20°W. and dips very steeply towards the east; the 'b' axis is very nearly vertical. The hornblende-schist passes at both margins into banded and striped hornblendic rocks, finally grading to the ordinary siliceous granulites through striped quartz-feldspar-hornblende-granulite. The marginal varieties form a gradual transitional series from the hornblende-schist to the ordinary Moine rocks, between which it is in consequence impossible to draw a dividing line.

Further south on Creag Dail na Méine two large hornblendic sheets and four smaller ones are exposed. The interrelationships of the rocks in this area can be best presented by describing the details of a natural section (see Fig. 2) across the two large hornblendic sheets exposed on the southern slope of Creag Dail na Méine (see map Fig. 1). Beginning at the west-south-western end of the section the ordinary siliceous granulites, characterised by thin streaks of hornblende, grades through striped hornblendic rocks of typical Durcha type to a band of hornblende-schist about two yards wide. The hornblende-schist /

schist is perfectly foliated, the strike of the foliation planes being north-north-west - south-south-east and their dip toward the east at an angle of 70°. It is usually cut by quartz veinlets, lenses and nodules that cross the foliation. Adjacent to the hornblende-schist and to the north-east of it, there is a zone, about 26 yards wide, of quartz-feldspar-hornblende-granulites; these rocks consist of greyish granulite with bands and streaks of pinkish feldspar and quartz, and lines of dark hornblende. In addition, the rocks are also more often than not conspicuously banded owing to an alternation of lamellae relatively rich in dark minerals (chiefly hornblende with subordinate epidote) and feldspathic material; this gives the rocks a typical striped appearance in the field. East-north-eastward of the latter zone is another band of hornblende-schist, some ten yards across, in which the schists are characterised by minor folds that are usually very conspicuously marked out by feldspathic layers. At the immediate contact between the feldspathic layers and the hornblende-schist relatively large prisms of hornblende are developed. The band of hornblende-schist in some places passes along the strike to striped quartz-feldspar-hornblende-granulite. Toward the north-east there is transition to the next zone, one of typical Durcha type about 15 yards wide, in which striped hornblendic rocks /

rocks alternate with layers of quartz-feldspar-hornblende-granulite. In the former rocks feldspathic materials occur either as interbanded parallel layers or as layers of connected augen in the hornblendic host which give the rock the appearance of an augen-migmatite. The strike of this zone is slightly west of north and it dips towards the east at an angle of 80°; the 'b' axis is nearly vertical. To the east-north-east of the latter zone lies the largest hornblendic sheet; this include two lenses of granulite. The section under description cuts through the southern extremity of one of these lenses and through the northern extremity of the other. The large hornblendic sheet, with an overall width of about 130 yards, consists chiefly of well foliated hornblende-schist with interlaminated white quartz-feldspar bands that range in width from a fraction of an inch to more than a yard. The strike of the sheet as a whole varies from slightly west of north to N.27°W., but the schist is characterised by complicated minor folds and small scale shear folds that are well displayed in three dimensions. Where the folding is prevalent the strike of the axes and the foliation planes is highly variable on a small scale, but taken as a whole, the fold-axes have a general north-south trend and pitch steeply towards the south. The minor folds are very /

very clearly displayed by the hornblende-schist because the white quartzo-feldspathic layers, laminae and augen serve as conspicuous structural guides. Within the hornblende-schist quaetzose bands are commonly drawn out into boudin-shaped forms (~~Fig.~~). The two lenses of striped quartz-feldspar-hornblend granulite are separated by a wedge of hornblende-schist which shows gradations to the granulites both along and across the strike. The granulites of the lenses are coarser grained than the corresponding rocks outside this sheet and very rich in pinkish feldspar.

The gradual and perfect transition both along and across the strike from fine grained hornblende-schist and amphibolite, through striped hornblendic rocks, quartz-feldspar-hornblende-granulite and siliceous granulite with hornblendic films and streaks to ordinary Moine granulite practically devoid of hornblende is a critical feature which originally led the former investigators (Read, 1925, pp. 18-20; 1926, pp. 144-7; J. Phemister, 1923, p. 108) to believe that these rocks are an integral part of the Moine Series and that they are of sedimentary origin. Later, however, Phemister showed preference for the hypothesis that the hornblendic rocks of Durcha type "may represent metamorphosed tuffs, lavas and associated minor intrusions, or they may be a series of sheets of banded igneous rocks" /

rocks" (Phemister, 1936, p. 20); and Y.C. Cheng (1944, p. 109), in dealing with the hornblendic rocks of the Bettyhill area, entertained a similar possibility. As there is no trace either of original calcareous or ferruginous dolomitic rocks or of intrusive rocks, lavas, tuffs or ashes preserved in the Rogart and Bettyhill areas, the true origin of the hornblendic rocks is very difficult to decipher, but judging from their field relationships and from the fact that rocks of Durcha type have been found by Read (1926, p. 145) in association with the Shinness limestone (peninsula of the Airde of Shinness, see Geol. Survey Sheet 102), the writer is inclined to favour the earlier views that these rocks represent calcareous sediments. In the case of the hornblendic rocks of Durcha type in the Rogart area emphasis should be laid on the nature of the quartzo-felspathic materials associated with the striped hornblendic rocks and present in the hornblende-schists. Some of these materials, especially the quartz-rich augen and lenses, do not represent the normal Moine granulite; they are in fact of migmatitic origin as Read (1926, p. 147) has already recognised. In deciphering the origin of these hornblendic rocks processes of migmatisation with the necessary complementary basification of adjacent portions must therefore be taken into account. It is thus not only possible but highly probable that the hornblendic rocks /

rocks now depart widely from their initial composition (cf. Backlund, 1936, 1943, 1946). There is, moreover, good evidence from other areas that similar hornblendic rocks have been developed from calcareous sediments, e.g. in the Haliburton-Bancroft area (Adams, 1910) and in Greenland (Backlund, 1936).

(b) Hornblendic Rocks of Igneous Origin

In addition to the hornblendic rocks of Durcha type of possible sedimentary origin, the Moines include hornblendic rocks that represent dolerite dykes that were emplaced before the general metamorphism. In the area investigated in detail by the writer only two such pre-foliation dykes were found. One of these is now represented by the hornblende-schist that outcrops 600 yards south by east of Càrn Liath, and the other, a chlorite-tremolite-schist, outcrops in the granulites three-quarters of a mile east of Morvich Lodge. The latter has the form of a bifurcating dyke. In the region further south hornblendic rocks of igneous origin are very abundant (see map, Fig. 1). Amongst these the writer has examined the well-exposed dyke on top of Creagan Asdale, and other bodies to the east of the eastern end of Loch a' Ghiubhais. The former, an epidiorite dyke about 25 yards wide and three-quarters of a mile long, cuts obliquely across the bedding of the Moine granulites. The middle part of this dyke is composed of massive epidiorite, but the marginal portions /

portions are foliated, the foliation cutting obliquely across the length of the dyke. The foliated marginal rock differs from the massive interior in being garnetiferous. Other horn-blendic rocks of igneous origin have been recorded by Read (1925, pp. 14-15) a quarter of a mile north of Maolanaidh Mòr; in the Garskelly Burn north-north-west of Maolanaidh Mòr; 500 yards north-west of Loch Lànsaidh; and on Creagan Dubh one mile north-east of Achvaich.

2. The Transformation of Hornblendic Moine Rocks to Rocks of Ach'uaine Type.

(a) The relationship between the distribution of rocks of Ach'uai type and the hornblendic Moine rocks.

A glance at the Geological Survey map of the Rogart are Sheet 103 (see Fig. 1) will suffice to show that whereas the Moine rocks to the south and south-east of the Rogart granodiorit include hornblende-schists of both sedimentary and igneous origir yet not a single example of hornblende-schist is depicted within the limits of the zone of migmatites, although the Moine rocks form the solid framework of this zone. On the other hand a suite of rocks recorded in the index to the Geological Survey Sheet 103 as "hybrids later than the regional metamorphism", and described in the corresponding Memoir (Read, 1925, pp. 45-51) as "Hybrid /

"Hybrid rocks of Ach'uaine Type", occur within both the zone of migmatites and the granodiorite, and to a lesser extent within the veined Moine granulites immediately to the south of the granodiorite. Although an example of hornblende-schist is shown on the map to outcrop less than a quarter of a mile beyond the limit of the zone of migmatites, yet exactly at and within the margin of the zone of migmatites the hybrid rocks appear. It would be a highly surprising coincidence if the pre-foliation hornblendic components of the Moine series did indeed die out before they reached what is now the margin of the migmatite zone, and if, just where they appear to die out, a suite of younger hybrid rocks commenced and continued the regional strike of the hornblendic rocks of the Moine series.

As long ago as 1893, in writing of the granitic rocks of the Rogart area, Hugh Miller recorded that "Parts of these granites are .... pseudomorphs or granite casts, preserving within portions of their mass, as replacement structures, the remains of the structure of the pre-existing rock". In 1925, in so far as the banded granites and streaky biotite-granite of the migmatite zone are concerned, Read concurred with this view. If granulite within the migmatite zone is so much altered as to assume the guise of granite, and the writer agrees with this interpretation, then obviously it is unlikely that the hornblendi rocks /

rocks of the Moine series would continue unaltered through this zone; they, like the granulites, might be expected to be transformed into other rock types. Is this not a clue towards the explanation of the so-called "Hybrids of Ach'uaine Type"? The present detailed investigation of these supposed "hybrid" rocks has, in fact, shown that they represent the hornblendic rocks of the Moine series in various stages of alteration. In the initial stages of change they became the repositories for the cafemic constituents displaced from the granulites during their granitisation and became transformed towards and even into rocks of ultrabasic type. Subsequently they were granitised and thereby further transformed through appinitic varieties towards or into rocks having the composition of granodiorite.

(b) <u>The transformation of hornblende-schist to rocks of Ach'uaine type in the zone of migmatites</u>.

Within the zone of migmatites there are many occurrences of rocks of Ach'uaine Type, and within some of these masses relics of hornblende-schists of Moinian age are preserved Some of these relict hornblende-schists obviously represent rocks of Durcha type, as may be judged from their similar banded and striped appearance. It is by no means always possible, however, to decide whether the residual hornblende-schist represents hornblendic rocks of igneous origin or rocks of Durcha type of probable sedimentary origin.

Relics /

Relics of hornblende-schist are best preserved within the rocks of Ach'uaine type that outcrop at no great distance from the outer margin of the zone of migmatites. As the inner gradational contact between migmatites and granodiorite is approached, the basic masses show an increasing degree of alteration, and the original structures are gradually lost.

On the map, Fig. 1, the outcrop of rocks of Ach'uaine type are numbered, and reference to these numbers will help to clarify the following description of specific examples.

On the top of Cnoc Bad a' Chrasgaidh, where the Moine granulites are least migmatised, relics of hornblende-schist have been found amongst the outcrops of rocks of Ach'uaine type. Thus the central portion on the eastern side of the basic body, No. 10, is composed of hornblende-schist and amphibolite, but when traced along the strike in either direction the hornblende-schist grades into much coarser grained rocks that are but slightly foliated and contain hornblende and pyroxene in varying proportions, sometimes with the addition of biotite. In the latter rocks it is possible to distinguish between hornblende and pyroxene in the field, for whereas hornblende is dark green the pyroxene has a relatively light yellowish green colour, and a more granular appearance. Locally the pyroxene and hornblende have a very patchy distribution, portions of the rock being composed /

composed essentially of pyroxene and others of hornblende. In the main, however, the rock is composed of roughly equal amounts of pyroxene, biotite and hornblende, being thus typical of the Ach'uaine type. One very noteworthy feature is that the dip and strike of the amphibolite and hornblende-schist agree perfectly with those in the surrounding siliceous granulites and migmatites, the strike being north-north-west - south-south-east and the dip very steep towards the east-north-east.

Half a mile to the south-west of the example just described, and to the south-west of a small fault-scarp along which six small outcrops of basic rocks appear, is a small exposure, No. 18, where again there is an association of hornblende schist with rocks of Ach'uaine type. At the southern end of this exposure there are striped hornblendic rocks of Durcha type that strike N.12°W. in conformity with the foliation of the neighbouring migmatites, and dip steeply eastwards. Such a steep easterly dip is characteristic of the rocks of Durcha type that outcrop in the Moine granulites to the south of the migmatite zone. When traced northwards the hornblendic rocks of the southern part of the exposure grade into coarser grained rocks of Ach'uaine type containing hornblende, pyroxene and biotite. In the central part of this outcrop patches of granodiorite occur.

The six small masses of basic rock that outcrop immediately /

immediately to the east of the fault-scarp, Nos. 12, 13 and 14, have a remarkable linear disposition that strongly suggests that they represent portions of a once continuous sheet of rock that became dissected as a result of localised granitisation. The rock composing these residual basic masses is related to the hornblende-schist in the Moine series both in its fineness of grain and in the fact that it is so strongly foliated as to be schistose. Mineralogically, however, it is related to the rocks of Ach'uaine type, being a pyroxene-biotite-hornblende-schist. This rock appears to represent an early stage of alteration of hornblende-schist into rock of Ach'uaine type. The rock between the residual basic bodies is a migmatite developed from the original belt of basic schists as a result of localised granitisation. In part the rock is a banded gneiss resembling some of the Finnish migmatised green schists. It has narrow alternating melanocratic and leucocratic layers that average about a centimetre in width. The leucocratic layers probably represent the more felsic and consequently the more easily granitised layers in the original schists, whilst the melanocratic layers, being now more basic than the Moinian hornblende-schist, represent basic fronts developed from the initially relatively basic and consequently less readily granitised layers. With advancing granitisation the migmatite has assumed a more homogeneous /

homogeneous appearance and is best described as a coarse grained diorite. Locally, where patches of actual granodiorite have developed, the associated migmatitic rock is even coarser grained including hornblende prisms that measure up to 3 x 2 cms. These coarse grained rocks form members of the appinite suite, and grade from hornblende-rich to more dioritic varieties. White granite veins cut all the rock types. The residual basic schist bodies within this basic migmatite and the banded gneisses all strike in a north-easterly direction and dip to the south-east, thus following the regional strike and dip of the Moine rocks of this region. The residual masses of basic schist, together with the associated migmatites, exhibit many resemblances to those hornblendic rocks of Durcha type that show transitions through striped hornblendic rocks and quartz-hornblende-granulites to the more normal granulites of Moinian type. Indeed a comparative field study strongly indicates that on migmatisation the hornblende-schist of such an association is transformed to the basic pyroxene-biotite-hornblende-schist, whilst the transitional types give rise to the associated migmatites.

Further westward, that is nearer to the passage from the zone of migmatites into the more homogeneous granodiorite, the basic masses exhibit more advanced stages of transformation. On top of Cnoc an Fhithich no fewer than 25 small outcrops of basic /

basic rocks occur within quite a small area, and continuing from here roughly along the regional strike towards the north-north-westward another seven small masses outcrop in the bed of Garbh-allt between Reidlin and Little Rogart. It is thus clear that these basic bodies not only have a tendency to occur in clusters, but also to appear along certain strike belts. This again conforms with the view that the basic masses are relict portions of original basic bands within the Moine granulites.

Among the 25 basic masses (Fig. 3) that outcrop on the summit of Cnoc an Fhithich, four (Nos. 19, 26, 32 and 43) occur as long narrow bands intercalated in and striking parallel to the foliation of the migmatised granulites. The majority of the basic masses on Cnoc an Fhithich, however, have an irregular shape of somewhat oval form. These oval-shaped bodies are but relics of much larger masses, as can be deduced from the fact that they are surrounded by zones of migmatite of dioritic composition developed from their peripheral parts. The original margins of the basic masses can still be seen where dioritic migmatite adjoins migmatised granulite. This retention of original form indicates that the migmatisation or granitisation of the outer portions of the basic rocks took place in the solid state. Considered as a whole, the basic masses on Cnoc an Fhithich are more profoundly modified by the processes of migmatisation /

migmatisation than are those previously described. Nevertheles the foliation that characterised the initial rock from which the present-day varieties were developed is still well preserved in some of the bodies (e.g. Nos. 31, 37).

Some of the basic masses that are but faintly foliated (Nos. 26, 32, 33) may represent migmatised epidiorites. No original hornblende-schist remains within these masses, but the main rock is a biotite-hornblende-pyroxene-schist in hand specimen not unlike that described from the region of the fault-scarp, but rather more lustrous and with the hornblende usually clustered along lines parallel to the foliation planes. The further stages of transformation exhibited by these lustrous bas schists follow contrasted routes. Thus, pink feldspar porphyro blasts appear within them and become segregated into veins which pass into networks of veins that traverse the basic masses in al directions (Fig. 4). When this feldspathic material appears the residual basic schist becomes still more basic, and large prisms of hornblende are developed in association with the felds par, thus giving rise to typical appinitic rocks (Nos. 32, 37, 39). In these rocks the basic schist weather more readily than the feldspathic material, and as a result the feldspathic net-works stand out as ridges, whilst the basic schist forms hollows and the rock thus receives a honeycombed appearance. With increasing /

increasing migmatisation the feldspathic veins become more granitic, and the granitic veins become increasingly wider until finally the rock assumes the form of agmatite in which the relics of basic schist remain as inclusions within granodiorite. The development of agmatite can best be studied on Creag a' Bhata and on the southern side of Creag na Chroiche, and the writer (Ma, 1948) has already presented a detailed field and petrological description of one of these agmatites that outcrops conspicuously (see pp. 145-164 of this thesis).

In this occurrence it is quite clear in the field (a) that as the replacement veins of granodiorite develop from the basic schist the displaced cafemic constituents become fixed in the residual schist relics, sometimes forming an ultrabasic hornblendite rim at their margin; and (b) that the subsequent granitisation of such basified schist has finally given rise to the series hornblendite-appinitic rocks-dioritic migmatite-granodiorite.

The most westerly mass of rocks of Ach'uaine type within the zone of migmatites outcrops in the bed of Allt Mor close to the arbitrary line drawn on the map to represent the position where migmatites pass into more homogeneous granodiorite. At the southern end of this outcrop, which measures about 80 by 40 yards, relics of slightly foliated rocks containing biotite, hornblende /

hornblende and pyroxene are exposed. The mass as a whole, however, is suffused with granitic material, in association with which large crystals of hornblende and biotite have developed from the residual basic rock. In a small ravine cutting through the middle of the mass a contact between the rocks of Ach'uaine type and striped migmatites is exposed; this contact, striking north-north-west - south-south-east and dipping towards east-north-east represents the original contact between a basic rock, now transformed to rocks of Ach'uaine type, and the Moine granulites, now transformed to striped migmatites, with which it was intercalated.

(c) Rocks of Ach'uaine type in the granodiorite.

Within the granodiorite there are four large and eleven small masses of rock of Ach'uaine type. The three large masses exposed around Loch Airidhe Mhor, Loch Airidhe Bheg and Corryachvrail in the southern part of the granodiorite lie on the continuation of the regional strike of the large hornblendic masses of Durcha type that are intercalated in the Moine granulites around Creag Dail na Méine about two miles to the south-east. Moreover, two (Nos. 73, 74) of the large masses of rocks of Ach'uaine type within the granodiorite have a definite sheet-like form, dipping into the granodiorite parallel to the foliation planes in just the same way that the hornblendic rocks of /

of sedimentary origin dip parallel to the bedding of the granulites. As will become apparent from the following detailed descriptions of the basic masses within the granodiorite, the frameworks of the large sheet-like bodies are older than the granodiorite. On any magmatic interpretation of the rocks of the Rogart area it would therefore be necessary to explain how older basic sheet-like masses came to be included within the granodiorite into which they now dip parallel to its foliation planes. To the view that the granodiorite and the rocks of Ach'uaine type are transformed Moine granulites and hornblende-schists respectively the inter-relationships present no difficulty. As the Moine granulites were granitised and approached the composition of granodiorite the displaced cafemic constituen became fixed in the initially more basic rocks - the hornblende-schists - which were in consequence gradually converted to rocks of Ach'uaine type. In a previous section of this thesis (pp.18-22 it was shown that towards the outer margin of the zone of migmatites relics of hornblende-schist, like that intercalated in the Moine granulites, are associated with and grade into rocks of Ach'uaine type. The first step in this transformation is the development of hornblende-biotite-pyroxene-schist. In the inner part of the zone of migmatites, as granodiorite is approached, the masses of Ach'uaine rocks no longer include relics of /

of hornblende-schists; alteration was here so intense that all the original hornblende-schist has been transformed to hornblend biotite-pyroxene-schist and coarser grained rocks of Ach'uaine type. It is not surprising, therefore, to find within the granodiorite that hornblende-schist is not represented amongst the masses of Ach'uaine type, and that relics of hornblende-biotite-pyroxene-schist are rare.

Indeed the alteration of the initial hornblendic rocks within the zone of granodiorite has been so intense that, in general, rocks of Ach'uaine type in which no vestige of the original foliation now remains form the starting point from whic the further evolution through appinitic rock varieties to granodiorite can be traced. In the following descriptions of some of the individual basic masses the evidence for these further evolutionary stages will be presented.

Commencing with the basic masses of Ach'uaine rocks exposed just within the southern margin of the granodiorite, the most westerly one, No. 75, is elongated parallel to the margin of the granodiorite, and its outcrop bifurcates towards the west It has a length of about 1500 feet and its greatest width is about 500 feet. The following is a description of a section across this body at its widest part. On the south-western side is a belt of rock about 65 yards wide which has a somewhat foliated /

foliated appearance due to the presence of abundant flakes of biotite orientated in planes that strike approximately from east to west and dip steeply northwards. Within this dark greenish brown rock (which may be described as a mela-syenodiorite) relatively large hornblende crystals are sporadically developed, usually occurring in clusters in association with feldspathic material. This marginal zone of rock is traversed by irregular patches and veins of pegmatite and aplite of which the contacts against the basic rock are sometimes sharp and sometimes gradational. The contact between the marginal rock and the granodiorite is irregular and lacking in sharpness. Adjoining this belt towards the north-east is a middle zone, approximately 25 yards wide, to which the marginal variety grades. This zone is composed of a very distinctive rock type containing large flakes of biotite, up to a centimetre across, set in a greyish green base of pyroxene with subordinate hornblende (i.e. a shonkinite). It differs from the marginal variety in the large size of the biotite flakes and in their lack of orientation. Farther towards the north-east the rock of the middle zone grade once again to the more hornblendic variety with smaller biotite flakes orientated along planes which here strike N.67^{o}W. and dip steeply towards the north-north-east. The marginal part of this north-eastern zone, adjoining the granodiorite, is cut by ramifying /

ramifying veinlets and patches of granitic material.

The basic body, No. 74, outcropping on the northern side of Loch Airidhe Mhòr is larger in size than the one just described and has a definite sheet-like form dipping into the granodiorite at an angle of 70°, parallel to the foliation of the granodiorite. It includes the same rock types as the body previously described and these types are arranged within it in a similar manner, there being marginal zones in which the biotite is orientated and a middle zone with unorientated biotite of larger size.

A section across the basic body, No. 74 (Fig. 5) as exposed at the southern end of the mass is as follows. The western contact between the basic body and the granodiorite is very well exposed (see Fig. 63) dipping westward at an angle of about 70°. A belt of rock about 15 yards wide on the western margin is rich in biotite, pyroxene and hornblende with an apparent foliation dependent on the orientation of the biotite. At the immediate contact with the granodiorite there is a narrow selvedge, about 2 yards wide, of biotite-schist which contains little or no pyroxene and hornblende, but is rich in large flakes of chocolate brown biotite.

The western marginal belt of slightly foliated mela-syenodiorite is ramified with irregular strings of granitic material /

material in connection with which hornblende crystals, measuring up to one or two centimetrs in length, have developed, giving the rock an appinitic appearance. Eastwards, this slightly foliated marginal zone grades to hornblendic migmatite that locally forms a belt about 3 yards wide along the line of section although it is quite irregularly distributed in so far as the basic body as a whole is concerned. Within this migmatite, residual patches of marginal rock remain. Further eastwards is another zone, about 10 yards wide, of the marginal rock variety with biotite flakes in parallel orientation. In this zone the biotite attains a very large size, reaching as much as one foot across. The latter rock grades eastwards into a zone about 40 yards wide of a coarse grained highly basic rock (a typical shonkinite) composed chiefly of pyroxene, with feldspar, large biotite flakes up to one or two centimetres across, and rare hornblende crystals. Here and there within this unfoliated coarse grained shonkinite there are patches of rock like the marginal varieties with flakes of biotite in parallel orientation. Along the eastern boundary of the basic body there is another belt of foliated rock with orientated biotite.

The foliated marginal rocks (mela-syendiorites) differ radically from the pyroxene-biotite-hornblende-schist and biotite hornblende-pyroxene-schist previously described (pp.21,24), in which the /

the foliation is a palimpsest structure, a relic of the hornblendic Moine rocks from which the schists were developed. The foliated marginal rocks of the two basic masses within the granodiorite owe their foliation to the orientation of the biotite flakes only. Under the microscope the other minerals can be seen to have a random orientation. As will be shown in the petrological section of the paper (p.83) the biotite is of late development, and it seems probable that the orientation of its flakes is to be attributed to growth under stress conditions dependent on an increase of volume within the rocks as a result of introduction of chemical constituents in excess of those displaced.

The third large basic body, No. 73, situated to the north of Loch Airidhe Bheg, resembles the two already described in being more or less lenticular in shape, but the distribution of rock types within it differs considerably. This mass is composed chiefly of a coarse grained rock (shonkinite) characterised by pyroxene and large flakes of biotite. At the contact on either side the rock is finer grained and contains hornblende in addition to pyroxene, but the marginal facies are not foliated as in the two examples previously described. Within the coarse grained central portion there is a development of white feldspathic spots (ranging from a few millimetres to

10 /

10 mm. in diameter) which are usually surrounded by prisms of hornblende. The white spots are frequently seen clustered together in patches, and as a result of differential weathering they stand out in relief from the rest of the rock (see Fig. 66) The coarse grained central portion is about 60 yards wide and is situated nearer to the western than the eastern boundary of the mass. The contacts against the granodiorite are not very clearly exposed, but judging from the general distribution of the rock types the mass appears to dip steeply towards the east.

Beside the three large bodies just described there are numerous basic masses scattered in the granodiorite between Loch Airidhe Bheg and the Dalmore Quarry. One series of such basic bodies, exposed in the low-lying ground to the north-east of Loch Airidhe Bheg, appears to form part of what was once a single narrow band. This band, No. 71, strikes N.30°W. and has a length of about 300 feet and a width of from 30 to 40 feet. In the middle part of this band pyroxene-biotite-hornblende-schistose rock is the closest approach that can be found to the original unaltered rock type. The strike of the schistosity is N.40°E. and the dip is steeply eastwards, so that the schistosity cuts across the dyke-like mass at an angle of about 70° to its length. At the south-eastern end of the band-shaped assemblage of basic bodies the rock is strongly granitised. Here in association with /

with patches of granodiorite, hornblendite and hornblende-pyroxene rock have developed as small-scale basic fronts (Fig. 6 Granitisation of the latter varieties has given rise to coarse grained basic appinitic rocks with stout hornblende prisms up to a square centimetre in size, to diorite, and finally to granodiorite rich in residual streaks of biotite and hornblende. Th process of granitisation is particularly well illustrated at the south-eastern end of the group of basic bodies on a smooth slab-like exposure of rock. On this slab granodiorite can be seen to have developed from rock of Ach'uaine type, while betwee these two kinds of rock a basic front of hornblendite appears. Traces of the transformed basic rock still remain in minute relics within the granodiorite, and a further stage of transform tion of the granodiorite itself is seen in the development of large pinkish porphyroblasts of potash feldspar within it.

About 100 yards north-east of the slab-like exposure i another linear series of small basic masses which can be linked together since they again appear to form isolated portions of a single narrow band, No. 72. This reconstructed basic band strikes from south-east to north-west parallel to the one previously described and has a length of 300 feet with a width of only 10 feet. The forms of this and the previously described basic band to the south-west suggest that they represent transformed /

transformed basic dykes or sills. Taken as a whole the basic band is intensely granitised, nevertheless a faint schistosity is still preserved within the residual coarse grained masses of rock of Ach'uaine type, and as in the previously reconstructed band the schistosity strikes in a north-easterly direction, cutting across the length of the band at a high angle and dipping to the south-east. To the south-east other small basic masses, Nos. 67, 68, 69 and 70, of much smaller size remain as scattered inclusions within the granodiorite. Most of these relics are of appinitic type with large hornblende crystals set in a feldspathic groundmass.

The largest basic mass, No. 78, within the granodiorite outcrops north of Ardaidh Chonachar and has a length of about half-a-mile. The contact relations between this mass and the surrounding granodiorite are fairly well exposed at the northern end of the mass on both sides of a small valley (Fig.64). Here it can be seen that in spite of its irregular outcrop the basic mass forms a thick sheet about 55 yards wide that dips into the granodiorite at an angle of about 50°. The contacts of this sheet with the granodiorite are by no means plane surfaces. They are, in fact, highly irregular, and the granodiorite at the lower contact contains many inclusions of the basic rock that vary in texture and decrease in size as the distance /

distance from the contact increases, until finally the granodiorite contains only small clots of hornblendite relics (Fig. 7). The basic sheet is composed mainly of a coarse grained massive appinitic rock containing squarish crystals of hornblende in a pinkish white base of feldspar with small amounts of pyroxene and biotite, but typical rocks of Ach'uaine type (and pyroxene-rich mela-syenodiorite) were found at the northern end of the mass. Further south the basic sheet dips more gently towards the east and much of the granodiorite has been eroded away from its surface. It is this erosion effect that has given rise to the highly irregular shape of the outcrop of this sheet.

Three smaller masses of basic rock outcrop in the neighbourhood of the thick basic sheet just described. Of these one is situated in Ardaidh Chonachar (No. 77), another to the north of Loch an Fheoir (No. 80). No. 79, which is fairly well exposed, displays the relationships between the various rock types very clearly. This basic mass covers an area measuring nearly 200 yards in length and 30 yards in width, extending from the top of the crag down to the bed of Torbreck Burn. The distribution of the various rock types within the body are shown in Fig. 8. The greater part of the mass is composed of a coarse grained rock of Ach'uaine type containing hornblende, biotite, and pyroxene (a biotite-rich mela-syenodiorite). At the south-western /

? Eastern

western corner a mass of feldspathic hornblendite, containing subordinate biotite and pyroxene, forms a broad rim more than 10 yards wide at its thickest part. The nearest approach to the parent rock from which these two varieties were developed is a medium grained hornblendic rock that outcrops in the bed of the Torbreck Burn. This rock has a bedded appearance and has a trend of N.10°.W. and a steep dip eastwards. Similar relics of hornblendic rock can also be found occasionally in the central part of the rock mass. The development of coarse appinitic rock as a transitional zone between the basic rocks of Ach'uaine type, and feldspathic hornblendite can be best seen in the river bed of Torbreck Burn and on the Crag at the northern margin of the mass. In the granodiorite to the southern margin of the basic mass inclusions of the basic rock are common. In this rock mass, No. 79, gradations from an initial hornblendic rock, through rock of Ach'uaine type to feldspathic hornblendite and then through appinitic varieties to hornblende-rich diorites and finally to granodiorite are well displayed. Patches of granodiorite and late veins of aplite and calcite are common throughout the body, and it is noteworthy that the aplite and calcite veins in the feldspathic hornblendite are usually rimmed by a narrow zone in which tremolite has developed at the expense of the hornblende.

(d) /

(d) Rocks of Ach'uaine type in the Moine granulites.

As Holmes and Reynolds (1947) have demonstrated in the Malin Head area of Co. Donegal, the basic components of a rock series that lies beyond the limits of migmatisation may undergo considerable chemical change, receiving enrichment of K, mafic constituents, Ti, P and Mn. Such rocks lie in the region of a peripheral basic front that develops beyond the limits of the migmatite front, as a result of the fixation of materials displaced from the latter. In the Rogart area evidence of a long-range basic front of a similar kind is found in some basic rocks that outcrop in the Moine granulites to the south of the granodiorite; four such masses outcrop on the crags to the south-west of Loch Iain Bhuidhe, whilst two more occur near Meall Clais nan Eath. These rocks are clearly sills and dykes that cut the bedding of the Moine granulites at a low angle, and their intrusive relationships to the Moine granulites are best displayed by masses Nos. 4, 6 and 7 to the south-west of Loch Iain Bhuidhe. Of these masses Nos. 4 and 6 are typical sill-forms trending parallel to the foliation of the Moine granulites. The basic rocks are themselves faintly foliated in the same direction.

No. 6 has an outcrop about 100 yards long and 10 feet broad at its widest part, whilst No. 4, intrusive in some pelitic granulites, has a maximum width of about 15 to 20 feet. No. 7, intrusive /

intrusive in siliceous granulites, has an oval-shaped outcrop about 13 feet long and 8 feet broad. The basic rocks in these masses are faintly foliated. The foliation follows that of the surrounding granulites, striking north-north-west and dipping east-north-east at an angle of about 15°. Two varieties of basic rock are apparent in the field. One is a fine grained biotite-pyroxene-rock with a little hornblende and feldspar, whilst the other is a medium grained pyroxene-biotite-hornblende-rock that is more feldspathic than the other variety. The basic masses are characteristically ramified with thin strings of pinkish feldspathic material but no granitic veining has been found.

(e) Summary of the evidence relating to the age of the rocks of Ach'uaine and Appinite types in the Rogart area.

In deciphering the age of the rocks of Ach'uaine type that are included within the zone of migmatites the following observations are of outstanding importance:

(i) The basic masses are usually concentrated along certain lines that agree with the regional strike, a feature which resembles the occurrence of hornblendic bands of Durcha type to the south of the migmatite area. Thus, for example, basic masses Nos. 12-18 are situated along a line that runs north-north-west - south-south-east, and in the area between Cnoc an Fhithich and Little Rogart there are no less than 36 basic masses (e.g. Nos. 19-55) along a north-north-west - south-south-west line.

(ii) /

(ii) Relics of hornblende-schist have been found in association with rocks of Ach'uaine type, e.g. Nos. 10 and 18, the strike and dip of the relict hornblendic rocks being in perfect conformity with that of the foliation of the surrounding migmatites.

(iii) In the early stages of alteration of hornblende-schist into rocks of Ach'uaine type the schistosity of the original rock is often still preserved, as examplified by the pyroxene-biotite-hornblende-schist in the basic masses Nos. 12, 13, and 14, and the biotite-hornblende-pyroxene-schist in the basic masses Nos. 31 and 37. The strike and dip of the foliation of these basic schists are coincident with those of the neighbouring migmatites.

(iv) Some of the basic bodies, e.g. Nos. 12, 13, 14, 19, 26, 32, 43 and 54, are clearly band- or sheet-like in form, whilst others, e.g. Nos. 23, 24, 28, 33, 56, 57, 58 and 65 &c., cut the foliation of the migmatites and may represent altered hornblendic bodies of igneous origin. After migmatisation bodies of the latter kind contain unfoliated rocks of Ach'uaine type with oval outlines which might quite easily mislead some observers into thinking that the unfoliated rocks were intrusions younger than the migmatites; but as the detailed field work has clearly shown, they have developed within the solid frameworks of the basic bodies which are really older than the migmatites.

The basic masses of Ach'uaine type in the granodiorite yield the following important evidences:

(i) Some of the basic bodies, e.g. Nos. 74 and 78 are clearly sheet-like in form and can be seen to dip into granodiorite.

(ii) At the margins of some of the basic sheets, e.g. No. 78, inclusions of the basic rocks occur within the immediately adjoining granodiorite and rapidly die out away from the basic body.

(iii) /

(iii) In the schistose basic rocks that remain as relics within the rocks of Ach'uaine type the strike and dip of the foliation are parallel to those of the adjoining granodiorite, and in Nos. 71 and 72 cut across the length of the dyke-like basic mass at a high angle.

(iv) Apart from the secondary foliation in masses Nos. 74 and 75, dependent on the orientation of biotite flakes only (see pp. 29-32), no foliation can be seen in the coarser grained rocks of Ach'uaine type that have developed as basic fronts and granitisation products from the original schistose rocks.

Conjointly these observations prove that the solid framework of the basic bodies was in existence before the migmatites and granodiorite and even before the dynamic metamorphism that gave rise to the schistosity of the original hornblendic rocks and the relict schistosity that remains in some of the rocks of the Ach'uaine type. If the petrological evidence be followed and the rocks of Ach'uaine type be correlated with the hornblendic rocks of Moine age, then it is clear that the solid framework of the basic bodies is not only older than the granodiorite, but is actually older than the Moinian foliation. The present-day mineralogical dress of these bodies as rocks of Ach'uaine type, is both younger than their solid framework and post-tectonic. The rocks of Ach'uaine type are in fact, as the field evidence shows, the transformation products of hornblendic rocks older than the Moinian foliation.

This /

This transformation is to be correlated with the granitisation and migmatisation of the Moine granulites that resulted in the development of migmatites and ultimately in granodiorite. Similar inter-relationships have been indicated by Backlund (1943) in the Pre-Cambrian of Fennoscandia. In the early stages of transformation highly basic and ultrabasic rocks - rocks that will be shown in the petrological section of this paper to be members of a shonkinitic series - were developed within the original hornblendic rocks as basic fronts resulting from the fixation of mafic constituents and K displaced from the rocks undergoing granitisation. In the later stages of transformation these shonkinitic varieties themselves became granitised and, whilst structurally they became transformed to agmatites, petrologically they evolved through appinitic varieties to granodiorite.

In his two earlier Highland Memoirs (1925, pp. 5, 21, 45-51; 1926, pp. 9, 148-152, 154-166) Read assigned the 'Hybrid Rocks of Ach'uaine Type' together with the Lairg-Rogart granodiorite, Helmsdale granite and Migdale granite &c., to the 'Newer' granites of Scotland ('Newer' referring to post-regional metamorphism or perhaps to the final stages of metamorphism). In his later Highland Memoir (1931, pp. 193-4), however, he abandoned this grouping of Lairg-Rogart granodiorite and its associated /

associated migmatites with the Helmsdale granite in favour of the view that the Lairg-Rogart granodiorite was contemporaneous with the injection of granitic material of the Loch Choire Injection-Complex, thought to be of earlier (pre-Torridonian) age. Further, after examining some of the rocks of Ach'uaine type in the Loch Choire and Strath Halladale Injection-Complexes, he (1931, pp. 12, 140, 153-162, 165) tentatively interpreted the 'Hybrid Rocks of Ach'uaine Type' as a special type of "injection" rock. "In any event", he stated (1931, p. 162), "the whole history of the formation of the Ach'uaine Type may be connected with the injecting magmas throughout Sutherland". And later (1931, p. 165), he suggested that "The acid end of the series is possibly derived from the granitic injections of Loch Choire or Strath Halladale, so that these hybrids may be a special facies of injection-rocks".

As to the derivation of the ultrabasic end-member of the "hybrids", Read first believed it to have been "an ultrabasic rock or magma of picritic or pyroxenitic composition" (1925, p. 5). In 1926 (p. 9) he suggested that the initial ultrabasic rock "seems to have been ...... scyelite or hornblende rock", and (1926, p. 165) "that the true ultrabasic end-member of this hybrid-series is represented by the biotite-free ultrabasic rocks composed of olivine and pyroxene and described on p. /

p. 159". Later, he withdrew scyelite from the hybrid series (1931, p. 169) and considered that "The ultrabasic rocks forming one end of the hybrid series are most likely represented by olivine-pyroxene-hornblende-rocks" (1931, p. 165). The problem as to whether or not the ultrabasic end-member had consolidated before the "injection" of acid material was left undecided (Read, 1931, pp. 12, 165-173).

In discussing the "age and affinities of the Morvern-Strontian 'Granite'", MacGregor and Kennedy (1932, pp. 116-9) have given a clear summary of the time-sequences (a) for the 'Hybrid Rocks of Ach'uaine Type, the period of regional granitic injection, and the intrusion of the Lairg-Rogart granodiorite; and (b) for the Appinitic suite and the Morvern-Strontian 'Granites' of the South-western Highlands. These sequences are as follows:-

Read's Sutherland time-sequence:

(1) Intrusion of ultrabasic hornblende-pyroxene rocks or of ultrabasic magma.

(2) Pre-Torridonian regional injection of Moine Schists by acid pegmatitic and granitic magma, locally derived from the Lairg-Rogart granodiorite. Production of 'Hybrids of Ach'uaine Type' where the injecting magma encountered intrusions of ultrabasic rock or ultrabasic magma.

(3) Shearing of ultrabasic hornblende-pyroxene rocks (and of locally uninjected Moine Schists in which they are intruded) by post-Cambrian movements connected with the Moine thrust.

MacGregor /

<u>MacGregor and Kennedy's South-western Highland time-sequence</u>

(1) Regional injection of acid pegmatitic magma.

(2) Intrusion of ultrabasic to acid igneous rocks (Appinitic-Lamprophyre Suite).

(3) Intrusion of Morvern-Strontian 'Granite' of Caledonian, probably Lower Old Red Sandstone, age.

As may be gathered from these two sequences, the differences between Read on the one hand and MacGregor and Kennedy on the other are in respect of (1) the relative ages of the ultrabasic intrusions and the regional "injection" of the Highlands; and (2) the relationship between the Lairg-Rogart granodiorite and the regional granitic "injection".

In the light of the present study, the writer, in agreement with Read's conclusion, has found that the pre-existing basic rocks antedate the regional migmatisation of the Highlands and that the rocks of Ach'uaine and appinitic types are indeed "a special type " of the migmatites. The form and structure of some of the pre-existing hornblendic bodies of igneous origin, after alteration by the migmatisation process (see p. 40) may have misled MacGregor and Kennedy into believing that these bodies cut the migmatites (injection-gneisses).

As to the latter point, the writer has been able to compare the migmatites of the Rogart area with those of the southern end of the Loch Choire Complex; he has found that the rocks /

rocks in both complexes are essentially identical, and has therefore no hesitation in correlating them as having been formed during the same period.

In recording the inclusions in the Morvern-Strontian 'Granite', MacGregor and Kennedy observed that "The large masses indicated on Fig. 1, consist of coarse-grained basic appinite. The xenolithic nature is clearly seen at several localities but specially on the south shore of Loch Sunart near Achleek, where a large mass of appinite is cut by veins from the surrounding granodiorite", (1932, p. 114). This so-called xenolithic nature of the appinite led them to conclude that "the appinites are undoubtedly earlier than the granite-komplex, and are not intrusive into it as suggested by Scott after his examination of the Loch Sunart occurrences" (1932, p. 114). This xenolithic occurrence of the appinite in the granodiorite is comparable with the writer's observation on the marginal part of basic mass No. 78, where inclusions of appinitic rocks occur abundantly. The writer has found that the pre-existing basic rocks were earlier than the emplacement of the granodiorite but that rocks of appinitic composition were made from them during the process of granitisation.

Thus the time-sequence established according to the Rogart evidences is as follows:

(1) /

(1) Basic intrusions and lime- and magnesia-bearing sediments of earlier age than the metamorphism of the Moines.

(2) Moine metamorphism by which the rocks of (1) are transformed into epidiorite, amphibolite, hornblende-schist and hornblendic rocks of Durcha type.

(3) Regional migmatisation and granitisation, whereby the hornblendic Moine rocks were first basified into basic and ultrabasic rocks (shonkinite —— mela-syenodiorite —— hornblendite) and then granitised with development of diorite, and finally granodiorite. Other Moine rocks (granulites, semi-pelitic and pelitic rocks) were granitised to granodiorite through various stages of striped migmatites.

The time interval between (2) and (3) was probably very short, migmatisation and granitisation being regarded as the culminating phase of the Moine regional metamorphism.

As to the absolute age of the Moine metamorphism, the time of emplacement of the different granite bodies and the time-relationship between the Moine metamorphism and the Moine thrust movement, there is still so much diversity of opinion amongst Highland geologists that the writer prefers at present to leave these problems without comment.

PETROLOGY

1. General Summary of Treatment

In a previous section of the thesis an attempt has been made to give a general picture of the field resemblances and relationships between the hornblendic components of the Moine, both sedimentary and igneous, and the basic masses of Ach'uaine type within the region of migmatisation and granitisation. In this section the petrological, mineralogical and chemical evidences are closely correlated with the field observations, for by this means alone can the problem as to the origin of the rocks of Ach'uaine type be completely solved.

In the following petrological descriptions the evolution of rocks of Ach'uaine type from the hornblendic rocks of the Moine Series will be traced by strictly following the gradational series already established by field observations. The petrology of the hornblendic rocks in the Moine Series will therefore be presented first, special attention being paid to the hornblendic rocks in the zone of veins which have undergone only a slight degree of migmatitic change. Next it is proposed to describe the relics of similar hornblendic rocks found in association with the rocks of Ach'uaine type, (a) within the basic masses in the zone of migmatites, and (b) within the granodiorite /

granodiorite. Such relict hornblendic patches are most commonly preserved within the basic masses that outcrop near the outer margin of the zone of migmatites, where the country rocks have suffered a relatively weak degree of migmatisation. The first sign of mineralogical transformation exhibited by those hornblendic relicts is the development within them of patches of greenish pyroxene which extend roughly along the foliation. With increase in the amount of pyroxene the hornblendic rocks grade, along their strike, into a coarsely granular rock, rich in greenish pyroxene, which closely resembles the shonkinite described by Weed and Pirsson from Montana (1895, 1895, 1900, 1905) and shonkinite (Basswood type) by Grout (1925). This shonkinitic rock will therefore be described next. It is well represented in association with the hornblendic rock in the basic mass, No. 10, which outcrops at the summit of Cnoc Bad a' Chrasgaidh.

In other basic masses, where relict hornblendic rocks are absent, shonkinite may form the main part of the mass; for example, it forms the middle zone of the large basic masses, Nos. 73, 74, and 75 around Loch Airidhe Bheag, Loch Airidhe Mhor and Corryachvrail. Shonkinite usually appears as a transitional type between the hornblendic rocks on the one hand and the mela-syenodiorites on the other; thus, in the large basic masses /

masses (Nos. 73, 74 and 75) the middle shonkinitic zone passes outwards, with every gradation, to a marginal zone of mela-syenodiorite. Mela-syenodiorite will therefore be treated next. It is the predominant variety amongst the basic rocks of Ach'uaine type, and it is extensively represented in all basic masses. It forms the bulk of several large basic masses such as Nos. 71, 72, 77, 79, 80, and constitutes the major part of the marginal zone of the basic masses Nos. 73, 74 and 75. In the basic mass No. 79 where no large mass of shonkinite occur mela-syenodiorite forms the main part of the body. In the basic masses in which shonkinite is not widely represented, shonkinite may nevertheless occur as isolated, small irregular patches, haphazardly distributed as relics within the mela-syenodiorites.

The rocks which form the margin of the basic masses will next be described. Where the rocks of Ach'uaine type adjoin the granodiorite, the mela-syenodiorites (more rarely shonkinite) grades to a suite of rocks that is characterised by a marked development of large squarish crystals of hornblende. These rocks form a series which ranges from hornblendite through feldspathic hornblendite to appinite. Hornblendite in the strict sense, has a purely local and restricted occurrence, appearing as rims at the periphery of residual patches of mela-syenodiorite /

mela-syenodiorite and as small clots, isolated within the granodiorite. In the south-western corner of the basic mass No. 79, which is composed mainly of mela-syenodiorite, a belt of feldspathic hornblendite, about ten yards wide, shows perfect gradation from the central mela-syenodiorite to a marginal zone of appinitic rocks.

The appinites have a much wider distribution than the hornblendites. They occur chiefly as marginal facies of the basic masses; in the basic mass No. 79 the appinitic marginal variety can be well seen in the river bed of Torbreck Burn, and at the northern margin of the mass, where it is well exposed on top of a small hill. Appinites also flank the middle shonkinite zone of the basic mass No. 73, north of Loch Airidhe Bheag. On the western side of the mass appinites reach a width of thirty yards, while on its eastern side they are only about ten yards wide. Appinites are also found in the marginal parts of several other basic masses such as Nos. 14, 71, 72, 74 and 75. In the basic mass No. 78 appinite forms nearly the whole of the mass.

Finally, the appinites are seen to grade to more and more granitic-looking rocks. Diorites, which form a passage type between appinites and granodiorite, are not well developed in the basic masses within the zone of granodiorite, but they are /

are very widely represented within the basic masses in the zone of migmatites. The granodiorite associated with the basic masses is a coarse grained greyish rock, with abundant biotite and hornblende. It contains orthoclase porphyroblasts which may reach a length of one inch.

From the following summary of the relationships between the rock varieties that constitute the basic masses of Ach'uaine type it will be seen that they form a gradational series from the initial hornblendic rocks of the Moine to the final granodiorite:

Hornblendic Moine rocks ⟶ Relict hornblendic Moine rocks associated with Ach'uaine types ⟶ shonkinite ⟶ mela-syenodiorite ⟶ hornblendite and feldspathic hornblendite ⟶ appinites ⟶ diorite ⟶ granodiorite.

In the following pages the various rocks will be described in this order. In the earlier stages of change the initial hornblendic Moine rocks become progressively basified until locally they eventually attain the composition of hornblendite. The subsequent changes from hornblendite through appinitic varieties and diorite to granodiorite represent stages of progressive granitisation. These two contrasted serial changes - basification and granitisation - may be schematically represented as follows:

BASIFICATION /

← BASIFICATION SERIES →

Hornblendic Moine rocks → Relict hornblendic Moine rocks associated with Ach'uaine types → Rocks of Ach'uaine type → {Shonkinite; Shonkinitic mela-syeno-diorite; Mela-syeno-diorites} → Hornblendite and Feldspathic hornblendite

← GRANITISATION SERIES →

{Hornblendite and Feldspathic hornblendite} → Appinite → Diorite and Quartz-diorite → Granodiorite

2. Hornblendic rocks of the Moine Series

The following descriptions of the hornblendic rocks are based chiefly on an examination of the specimens collected by the writer from the area he has examined in detail. In addition, he has also examined the 26 Survey slices, previously studied by Professor Read, of the hornblendic rocks depicted on the Geological Survey Sheet 103. Some of these thin sections in the Survey collection represent hornblendic rocks from the area to the south of that examined by the writer. The writer is much indebted to the officers of the Geological Survey for the privelege of allowing him to examine these thin sections.

(a) Hornblendic rocks of probable sedimentary origin.

The members of this group of rocks can be classified according to the percentage of hornblende they contain, since they vary from dark hornblendic rocks, through striped and banded hornblendic intermediate types, to the ordinary siliceous granulites with hornblende streaks.

The dark hornblendic components appear macroscopically either as fine-grained, well foliated hornblende-schists or as massive speckled amphibolites. In thin section (330, 529, 1330, 1630, 3130, 22786*, 22803*) they can be seen to be compose dominantly /

*-Geological Survey slices.

dominantly of closely packed and aligned prisms and grains of hornblende (Fig. 13), with a pleochroism of X = greenish yellow < Y = dark green < Z = deep bluish green and $Z \wedge C$ - ca 24^{o}. The feldspar is predominently andesine An_{32}, and it is either moderately sericitised or fresh. It sometimes exhibits a fine natiperthitic texture, and the orthoclase lamellae of the anti-perthite are sometimes continuous with the larger units of orthoclase that grow around the marginal part of the andesine (1629, 1330). Pyroxene is sometimes present, and is particular-ly well developed within the orthoclase-rich areas. It is greenish in colour and occurs as grains and poikiloblastic crystals closely associated with hornblende (529, 3130) (Figs. 14 and 15). The hornblende here is much paler in colour than that occurring in the ordinary hornblendic rocks without pyroxene. Quartz occurs as scattered grains. Epidote, usually slightly brownish in colour, occurs as small grains and is most commonly present in the finer grained bands. Accessories are sphene, zircon, iron-oxides and chlorite.

Specimen No. 1330 has been chosen for chemical analysis, the results of which, together with the normative composition and the mode of the rock, are recorded in Table I. As compared with the epidiorites (Table II), the hornblende-schist of Durcha type shows a very high content of alumina relative to silica.

Table /

TABLE I

Hornblende-schist No. 1330 from the large hornblendic mass at the summit of Creag Dail na Méine.

	Percentages	Mol. Props.
SiO_2	51.88	.8638
Al_2O_3	17.24	.1691
Fe_2O_3	3.46	.0217
FeO	5.70	.0793
MgO	5.58	.1384
CaO	8.22	.1466
Na_2O	3.06	.0494
K_2O	2.21	.0235
H_2O + 105°C	1.42	-
H_2O - 105°C	.19	-
CO_2	Nil	-
TiO_2	.91	.0114
P_2O_5	.08	.0006
MnO	.14	.0020
	100.09	1.5058

Analyst: W.H. Herdsman

Normative Composition

or		13.05
ab		25.90
an		26.75
di	($CaSiO_3$	5.62
	($MgSiO_3$	3.61
	($FeSiO_3$	1.63
hy	($MgSiO_3$	10.15
	($FeSiO_3$	4.63
ol	(Mg_2SiO_4	.01
	(Fe_2SiO_4	.06
mt		5.02
il		1.73
ap		.20
water		1.61
		100.06

Mode

quartz	3.62
plagioclase	30.37
orthoclase	9.49
hornblende	54.77
sphene	1.15
epidote, ore, apatite &c.	.70
	100.10

von Wolff Values

Q = −0.16
L = 64.28
M = 35.88

The striped and banded hornblendic intermediate types are characterised by a regular alternation of greyish quartz-feldspar layers and dark greenish black hornblendic layers. In thin section (829, 1029, 1329, 1330b, 22729*, 22731*) the dark bands can be seen to consist chiefly of aligned prisms of hornblende with subordinate feldspar, quartz, and epidote (Fig. 16). They are closely similar to the hornblende rocks described above and contain a similar hornblende with X = greenish yellow < Y = dark green < Z = greenish blue and $Z \wedge C$ = ca 24°. Oligoclase is the dominant feldspar, but orthoclase may occur in considerable amount in some slides where the rocks come from near the margin of the zone of migmatites and granodiorite, as for instance, from the hornblendic masses on the summit of Creag Dail na Méine and west of Ach' Torra' Dhamh (22731*, 1330b) Within the orthoclase-rich areas (1330b, 22730*) the pyroxene usually grows on the margins of the hornblende and from a comparative study of different crystals it can be seen that pyroxene gradually encroaches into the hornblende, until finally only patches of hornblende remain as inclusions within the pyroxene. This development of pyroxene at the expense of the hornblende together with the abundance of orthoclase in the marginal /

* Geological Survey slices

marginal part of the zone of migmatites and granodiorite may indicate that these hornblendic rocks, situated in the 'zone of veins', have already undergone a slight change of composition, although it is imperceptible to the naked eye. Moreover, Read (1925, p. 19) has recorded an allied hornblendic rock which contains abundant pyroxene and biotite from the Allt Ach' a' Bhathaich, two miles above Ascoile, Strath Broth Brora. In thin section (22782x) it is seen to be composed of hornblende, pyroxene, biotite, oligoclase-andesine and quartz, which is indistinguishably like some of the mela-syenodiorites of Ach'uaine type. Accessories in these dark bands are sphene, orthite, iron-oxides, zircon, biotite and apatite. The light coloured layers are indistinguishable from the ordinary siliceous granulites, being composed of mosaic-like aggregates of quartz and oligoclase dotted with scanty accessories. These quartzo-feldspathic bands may sometimes degenerate into rows of augen-shaped forms. In thin section (1029) these augen are seen to be composed of fine grained aggregates of oligoclase with large irregular individuals of quartz.

The least hornblendic members of this series are glassy-looking granulites, characterised by regular dark hornblendic streaks parallel to the foliation. In thin section (230 /

x Geological Survey slices

(230, 329, 629, 2230, 2330, 22788*, 22789*, 22791*) the rock is found to consist of a mosaic of strained grains of quartz and feldspar with scattered biotite flakes. The biotite has X = straw yellow; Z = brown with greenish tinge. The feldspar is usually oligoclase An_{27}, commonly somewhat sericitised and replaced by epidote and clinozoisite. In this quartzo-feldspathic base there are streaks and films composed of hornblende or of hornblende with a subordinate amount of epidote and pyroxene.

(b) Hornblendic rocks of igneous origin.

Typical epidiorite forms the central portion of the Creagan Asdale dyke and the small dykes 300 yards east of the eastern end of Loch a Ghiubhais. At both localities it is a dark, massive, medium grained rock, speckled with white feldspar In thin section (68, 22797*) it is found to be composed dominantly of aggregates of hornblende built up of small prisms and blades, which tend to coalesce into somewhat sieved large crystals of about 1-2 mm. in size. The pleochroism of the hornblende is x = yellow $<$ Y = brownish green $<$ Z = green with a brownish tinge, and $Z \wedge C$ = ca 24°. As noted by Read the hornblende aggregates usually wrap around the tabular feldspar crystals /

* Geological Survey slices

crystals in a manner which seems to indicate an original ophitic texture (Figs. 17 and 18). The feldspar is andesine which forms large euhedral and subhedral crystals from one to 1.5 mm. in length. They are usually sericitised, particularly in their middle portions, which are commonly strongly clouded with sericite. Occasionally the andesine exhibits strain shadows. Black iron-oxide is a very noteworthy accessory. It usually occurs in the middle of the hornblendic areas, and is always coated with a narrow rim of nearly colourless sphene. Quartz is present as small grains, commonly as inclusions sieving the hornblende. Other accessories are orthite, chlorit and very rare apatite.

At the marginal part of the dyke the rock has been converted into a typical hornblende-schist, with very well developed schistosity. In thin section (28, 48, 78, 22794*) the hornblende occurs as large and stout aligned prisms with pleochroism of X = yellow with a greenish tinge < Y = green with a brownish tinge < Z = greenish brown and $Z \wedge C$ = ca 20°. It is usually sieved with quartz grains. The feldspar is oligoclase, An_{23}, which builds euhedral to subjedral crystals. It differs markedly, however, from the andesine in the central part of the dyke in being clear. In one slide (48), however, the feldspar is

* Geological Survey slice

is seen to be in part replaced by clinozoisite. In some of the thin sections (78, 22794x) there occur large skeletal crystals of garnets, about 4 mm. in diameter, which enclose grains of quartz, feldspar, hornblende and iron-oxide in poikilitic fashion (Fig. 19). Iron-oxide, rimmed with sphene is very abundant in many of the slices.

Read (1925, pp. 16-17) has recorded the development of new sodic oligoclase and biotite in the rocks of Black Water dyke, three-eighths of a mile north-west of Balnacoil Lodge, north of the Rogart migmatite area. He has also recorded the presence of epidote in the hornblende-schists from the dyke of Garskelly Burn and a quarter of a mile north of Maolanaidh Mòr (4260), south of the Srath Càrnaig, and of pyroxene- and biotite-bearing types of hornblendic rocks from 250 yards east of Lochan Dubh, north of the river Brora, and in the Corrish Burn, 300 yard up from the river Brora. The latter pyroxene-rich variety closely resembles some of the rocks of Ach'uaine type. Thin sections (22765x, 22754x) of the latter rock show the pyroxene to be monoclinic, to vary from pale greenish to colourless, and to occur as sieved prisms intergrown with hornblende.

For the sake of comparison with the analysed basic rocks of Ach'uaine Type, three chemical analyses of epidiorites of

x Geological Survey slices

of post-Moinian and pre-migmatisation age from the Northern Highlands have been collected from the Geological Survey Memoirs, and are tabulated in Table II. One of these chemical analyses is of an epidiorite from Central Sutherland (Read, 1931, p. 74), and another from the Carn Chuinneag complex of Ross-shire (Flett 1912, p. 95). Chemically, the first example was regarded by Read as being closely similar to norite. The other two examples resemble olivine-free gabbros, and were regarded by Flett as having a composition "on the boundary line between gabbros and augite diorites" (1912, p. 96).

TABLE /

TABLE II

	1	2	3
SiO_2	50.02	54.51	52.84
Al_2O_3	15.36	12.26	14.06
Fe_2O_3	2.29	1.64	1.73
FeO	8.08	7.60	8.38
MgO	7.76	6.89	5.55
CaO	8.81	8.80	8.72
Na_2O	2.94	2.37	2.90
K_2O	1.30	1.85	1.74
H_2O +105°C	1.01	0.94	1.15
H_2O -105°C	0.16	0.04	0.08
CO_2	0.12	0.36	-
TiO_2	1.80	1.74	2.19
P_2O_5	0.14	0.78	0.29
MnO	0.18	0.32	0.25
FeS_2	0.19	0.20	0.14
Cr_2O_3		0.03	0.05
(Ni, Co)O			
	100.16	100.33	100.07

von Wolff Values

1. Q = −3.34, L = 54.82, M = 48.50
2. Q = 6.22, L = 45.64, M = 48.14
3. Q = 2.73, L = 52.92, M = 44.36

1. Epidiorite. Intrusion in Moine series 160 yards west of Loch Staing, Altnaharra, Sutherland. One-Inch Geol. Surv. Sheet 108, Scotland (858. Anal: B.E. Dixon). M.G.S. 'Central Sutherland, 1931, p. 74. S.25690.

2. Epidiorite, 'Biotite-amphibolite'. Marginal facies of the Carn Chuinneag Complex, intrusive in Moine Series, 785 yards east of north of Carn Dubh, Ross-shire. One-Inch Geol. Surv. Sheet 93, Scotland (233. Anal: W. Pollard). M.G.S. 'Ben Wyvis', 1912, p. 95. S.11790.

3. Epidiorite, 'biotite-amphibolite'. Marginal facies of Carn Chuinneag Complex, intrusive in Moine Series. Middle Glen, south side of Glen Diebidale, Ross-shire. One-inch Geol. Surv. Sheet 93, Scotland (238. Anal: E.G. Radley). M.G.S. 'Ben Wyvis, 1912, p. 95. S.11792.

3. The Evolution of Basic Fronts

(a) Relics of hornblendic rocks of Moine type.

Two examples of hornblendic rocks of Moine type which occur as relics within the basic masses of Ach'uaine type will be described here. Of these one is an altered hornblendic rock collected from the basic mass No. 79, that outcrops east of Creag na Pairce within the granodiorite. The other, a slightly foliated rock which contains pyroxene patches, comes from the eastern portion of the basic mass No. 10, which outcrops at the summit of Cnoc Bad a' Chrasgaidh near the outer margin of the zone of migmatites.

In hand specimen, the relict hornblendic rock from the basic mass No. 79 is a fairly massive rock which resembles the hornblendic Moine rocks of igneous origin. In thin section (1, 125, 3014) it is seen to consist mainly of prisms of hornblende with interstitial areas of feldspar (Fig. 20). The hornblende has a much lighter colour than the ordinary green hornblende in the hornblendic Moine rocks, its pleochroic scheme being X = nearly colourless with a greenish tinge $<$ Y = light green $<$ Z = green, and $Z \wedge C = 21^{\circ}-26^{\circ}$. The hornblende prisms are usually closely packed together in a similar pattern to that which characterises the epidiorites. Oligoclase, An_{27}, occurs as /

as euhedral tabular crystals and as subhedral aggregates. It is either fresh or slightly sericitised and occasionally shows strain-polarization as in the epidiorites. Quartz occurs as rounded or irregular granules either as sieve-like inclusions within the hornblende or within the feldspar. Orthoclase is very rare; where present, it occurs around the marginal part of the oligoclase crystals, against which it shows an irregular contact. Greenish brown biotite flakes are often seen intergrown with the hornblende prisms. Calcite, which appears as an alteration product of the hornblende, is very abundant. Other accessories are apatite, chlorite and iron-oxides.

Specimen No. 3014 has been chosen for chemical analysis, the results of which, together with the normative composition and the mode of the rock are recorded in Table III.

TABLE /

TABLE III

Relict Hornblendic rock No. 3014, from the basic mass No. 79 east of Creag na Pairce.

	Percentages	Mol. Props.
SiO_2	56.92	.9477
Al_2O_3	9.16	.0899
Fe_2O_3	1.02	.0064
FeO	3.96	.0547
MgO	12.58	.3120
CaO	9.15	.1632
Na_2O	3.32	.0536
K_2O	.64	.0068
H_2O+ 105°C	1.19	-
H_2O- 105°C	.08	-
CO_2	1.42	.0323
TiO_2	.46	.0058
P_2O_5	.09	.0006
MnO	.12	.0017
	100.08	1.6424 (without CO_2)

Analyst: W.H. Herdsman

Normative Composition

Q		4.24
or		3.78
ab		28.10
an		8.21
di	($CaSiO_3$	11.54
	($MgSiO_3$	8.74
	($FeSiO_3$	1.63
hy	($MgSiO_3$	22.58
	($FeSiO_3$	4.21
mt		1.48
il		.88
ap		.20
cc		3.23
water		1.27
		100.09

Mode

Quartz	3.05
Plagioclase	28.08
Orthoclase	2.28
Hornblende	58.85
Biotite	3.37
Calcite, Apatite, Ore &c.	4.34
	99.97

von Wolff Values

Q = 2.24
L = 36.60
M = 61.16

In hand specimen the hornblendic rock fron Cnoc Bad a' Chrasgaidh is a dark greenish black slightly foliated rock, with greenish brown patches elongated along the foliation. In thin sections (313, 313a) it is found to consist chiefly of closely packed prisms of subhedral to anhedral hornblende about 3 mm. in length and sometimes twinned, with X = pale yellowish green < Y = olive green < Z = green with bluish tinge, and $Z \wedge C$ = ca 20^{0}. The interstitial spaces are filled with quartz and andesine. Small needles of apatite form the main accessory. The rock closely resembles the amphibolites of sedimentary origin that outcrop in the zone of Moine granulites; it differs from the latter, however, in the presence of the small greenish brown patches in which the pyroxene is intergrown with the hornblende. The various stages of the growth of pyroxene can be traced, beginning with the development of a narrow rim of pyroxene at the margins of the hornblende crystals. In more altered examples the pyroxene is seen to have spread along the cleavage of the hornblende crystals, and to increase in amount until the greater part of the hornblende is finally changed to pyroxene. The pyroxene has very frayed and ill-defined boundaries against the hornblende, and is always dotted with fine grained, greenish brown aggregates of orthite, yellowish green chlorite /

chlorite flakes and calcite (Fig. 22). Sometimes the presence of deeper green patches with the pale greenish pyroxene is all that remains to indicate the former presence of hornblende. The pyroxene has in most cases adopted the crystal form and optical orientation of the hornblende; the relict hornblende where it remains can only be distinguished from the pyroxene by its slightly greater pleochroism and by its smaller extinction angle. It is thus seen that the hornblende is gradually replaced by pyroxene. Calcite sometimes forms large clear crystals in the neighbourhood of the pyroxene. Another noteworthy mineralogical change within the greenish brown pyroxene-rich patches is the development of orthoclase, which often forms large and irregular individuals that enclose the pyroxene and other constituents. The orthoclase also encloses patches of plagioclase, which are generally in optical continuity with larger units of plagioclase outside. The orthoclase is sometimes microperthitic. The plagioclase has a clear and more sodic margin where it comes in contact with the orthoclase, and myrmekite is also found along the contact.

Sphene is a very noteworthy accessory in the pyroxene-rich areas, where it occurs as large euhedral crystals about 1 mm. in length or as large skeletal forms seived with hornblende pyroxene and apatite (Figs. 21-22). The apatite crystals in the pyroxene-rich /

pyroxene-rich areas are of larger size than those in the hornblendic portions. Iron oxides are usually concentrated at the contacts between calcite and the other minerals, particularly hornblende.

The chemical composition, norm, mode of the relict hornblendic rock with pyroxene patches, No. 313, is recorded in Table IV.

TABLE /

TABLE IV.

Relict hornblendic rock with pyroxene patches, No. 313, from the basic mass No. 10 on the summit of Cnoc Bad a' Chrasgaidh.

	Percentages	Mol. Props.
SiO_2	54.86	.9134
Al_2O_3	5.47	.0537
Fe_2O_3	1.67	.0105
FeO	5.18	.0721
MgO	11.44	.2837
CaO	13.48	.2404
Na_2O	1.02	.0165
K_2O	.91	.0097
H_2O + 105°C	.92	-
H_2O - 105°C	.30	-
CO_2	.98	.0223
TiO_2	.34	.0043
P_2O_5	2.92	.0206
MnO	.19	.0027
	99.68	1.6276 (Exclude CO_2)

Analyst: W.H. Herdsman

Normative Composition

Q		14.14
or		5.39
ab		8.65
an		7.65
di	($CaSiO_3$	14.14
	($MgSiO_3$	10.10
	($FeSiO_3$	2.81
hy	($MgSiO_3$	18.38
	($FeSiO_3$	5.10
mt		2.43
il		.65
ap		6.92
cc		2.32
water		1.22
		99.81

MODE

Quartz	7.64
Orthoclase	4.84
Plagioclase	14.80
Hornblende	51.71
Pyroxene	11.10
Apatite	6.32
Sphene	1.83
Calcite	1.70
Ores &c.	.11
	100.05

von Wolff Values

Q = 10.22
L = 19.56
M = 70.20

(b) <u>Rocks of Ach'uaine Type</u>

The term "Rocks of Ach'uaine type" is used in this present investigation only to include (i) shonkinites and (ii) mela-syenodiorites.

(i) <u>Shonkinites</u>

The term shonkinite was originally defined by Weed and Pirsson (1895, pp. 415-416) as "... a granular plutonic rock consisting of essential augite and orthoclase .... with or without olivine, and accessory nepheline, sodalite, etcetra, may be present in small quantities". Later, however, these authors (1895a, 1900) extended its usage to include other alkali feldspar rocks in which mafic minerals predominate; thus they recorded a shonkinite from Yogo Peak, Montana, containing as much as ten per cent of andesine (two-sevenths of the total feldspar). In 1925 (pp. 472-480) Grout described a peculiar shonkinite related to some ancient Pre-Cambrian granite in Minnesota, in which sodic-plagioclase (albite and oligoclase) is associated with a high proportion of ferro-magnesian minerals including hornblende, pyroxene and biotite. By doing this he further broadened the usage of the term shonkinite. He remarked: "The term shonkinite has been found useful, however, in naming a number of other rocks, and the definition may well be broadened, as it was by the men who invented the term, to include /

include other alkali feldspar rocks in which mafic minerals predominate. Nephelite is certainly not to be considered essential" (1925, p. 472).

In this thesis the term shonkinite is retained for rocks like those to which it was applied by Weed and Pirsson (1895, 1895a, 1900, 1905). The majority of the shonkinitic rocks from the Rogart area, however, are more particularly comparable with those described by Pirsson (1900) from the Yogo Peak area in Montana, which contain a small amount of sodic plagioclase. It should perhaps be indicated here that under the term 'shonkinite of Basswood type' Grout (1925) has described rocks that consist essentially of hornblende and feldspar with which augite and biotite are sometimes associated. The feldspar varies from microcline and orthoclase to albite and oligoclase, with some perthitic intergrowths. The hornblende-rich variety is identical with the appinites as defined by Bailey, and the augite-biotite-hornblende type seems to be closely comparable with the mela-syenodiorites described in this thesis. According to the writer's opinion, the broadening of the term shonkinite to include so wide a range of rocks would lead to confusion from a petrogenetic point of view.

The shonkinites, as seen in the basic masses Nos. 73, 74, 75 around Loch Airidhe Bheg, Loch Airidhe Mhòr and Corryachvrail /

Corryachvrail, are particularly massive rocks that are rendered highly conspicuous by the presence of large biotite flakes with a criss-cross arrangement. In hand specimens they have a lustrous bronzy brown colour due to the reflection of light from the surface of the large biotite plates along which the rock splits. The biotites measure from 5 to 15 mm. in diameter and have a poikiloblastic texture, being mottled with numerous greenish grains of pyroxene and other constituents. In this poikiloblastic relationship between the large biotite flakes and the diopside crystals these rocks closely resemble the shonkinites of Yogo Peak, Montana (Pirsson, 1900, p. 480). In the basic mass No. 74, both toward the margin of the shonkinite belt and in its middle part, there is a development of schistosity dependent on the presence of parallel laminae characterised by large biotite flakes which alternate with others rich in pyroxene and feldspar. In these laminae optically continuou but disconnected flakes of biotite form interrupted films which may reach up to six inches or one foot in lenght (10, 12, 2124 and Figs. 23 and 24).

At Loch Airidhe Bheg in the basic mass No. 73, clouds of white spots appear in the dark matrix of the shonkinite. These spots are somewhat rounded in form and average from 2 to 10 mm. in diameter. They are commonly concentrated in small clusters /

clusters that give rise to a flowery pattern (Fig. 65). In this occurrence of white feldspathic spots in a dark matrix, these rocks closely resemble the Basswood Type Shonkinite described by Grout (1925). Around the white spots hornblende is conspicuously developed and the rock here acquires an appinitic composition (1420, 2320, 2420). Sometimes these clusters of white spots stand out from the r ock surface after weathering, as knobs (Fig. 66).

In thin section (11, 1022, 1023, 1223, 1523, 1621, 1922) the shonkinites are seen to consist of pyroxene, feldspar, biotite and hornblende, named in order of decreasing abundance. Accessories are olivine, apatite, sphene, calcite, orthite and iron oxides. The pyroxene has a very faint greenish colour. It forms short prisms with blunt or rounded terminations, or semi-rounded grains. Its maximum extinction angle ($Z \wedge c$) varies but little from 38°, indicating that it is diopside or diopsidic augite. Biotite builds large skeletal and poikiloblastic plates that enclose the pyroxene. These biotite plates may be quite lace-like in between the pyroxenes, but the disconnected portions all have a similar orientation, so that they have the appearance of being woven through the pyroxene (Figs. 25 and 26). In sections Nos. 1023, 1223, 1022, from the basic masses Nos. 74 and 75, the biotite has $\gamma = 1.602 \pm 0.001$, and is /

is pleochroic with X = yellowish brown and Z = dark greenish brown to almost opaque. These characters suggest that it is probably a magnesia-rich variety (A.J. Hall, 1941). In the shonkinites from the other basic masses (section Nos. 21, 1621), the biotite is a darker coloured variety with X = yellow, Y = Z = brown in thin section. Hornblende is not common in the shonkinites; it has X = pale greenish yellow < Y = yellowish green < Z = green and forms subhedral crystals that either margin the pyroxene or contain inclusions of this mineral. The hornblende sometimes exhibits a somewhat skeletal form sieved with apatite, biotite and feldspar.

In the shonkinites proper orthoclase is much more abundant than plagioclase, but by gradual increase in the percentage of plagioclase relative to the orthoclase all gradations can be found from shonkinites to mela-syenodiorites in which plagioclase preponderates over orthoclase. The plagioclase, which varies from albite-oligoclase (An_{15}) to oligoclase (An_{22}) (α = 1.5392) occurs as euhedral crystals, with lath-like cross sections, often enclosed within the orthoclase. The orthoclase, which is often perthitic, occurs in large poikilitic crystals within which prisms and grains of the dark minerals are enclosed (Figs. 27, 28 and 29). The melanocratic minerals are usually arranged quite haphazardly within the potash feldspar and /

and amongst them diopside is by far the most important, occupyin in an average example about 20% to 40% of the feldspathic areas. In some examples, 21, 513, the diopside is so abundant as to form about 90% of the rock which is then more correctly termed pyroxenite (Fig. 30). One very noteworthy phenomenon is that the feldspar in the pyroxenite and pyroxene-rich shonkinite is usually solely orthoclase; a similar relationship has been recorded by Weed and Pirsson (1900, p. 483) in their description of the shonkinites of Yogo Peak, Montana.

Olivine is a very rare constituent in the shonkinites (1022). When present it occurs as small grains that are coated with brownish and black iron oxides, including goethite, which also extend along the small cracks within the crystals. Apatite and sphene are very abundant accessories, the former building large stout prisms that are often crowded with bleb-lik and dusty inclusions. The sphene, which is pleochroic from pale brownish yellow to brown, occurs in large euhedral crystal and also as skeletal forms. It is usually associated with aggregates of pyroxene that are somewhat altered to calcite and obscure brownish amorphous materials. This suggests that the sphene may have developed to a certain extent at the expense of the pyroxene. Calcite, when present, is usually partly pseudomorphous after the pyroxene crystals, but it also forms small /

small veinlets that cut across the groundmass of the rock. When calcite comes in contact with the biotite, the latter exhibits corroded margins along which there is an accumulation of iron oxides. Less commonly, hornblende exhibits similar phenomena at its contacts with calcite.

The analysis, norm and mode of a shonkinitic rock, No. 1223, from the middle portion of the basic mass No. 75, east of Corryachvrail, are tabulated in Table V. This rock falls into a vacant subrange of the range Calcimric of the C.I.P.W. Quantitative Classification, having the symbol (III) IV. 1. 1(2). '3.1. It differs chemically from the shonkinite of Basswood type from Giants Range, Minnesota (Grout, 1925, p. 478) in its higher K_2O and MgO and lower FeO and Fe_2O_3. As compared with the analysis of shonkinite from Yogo Peak, Montana (Pirsson, 1900, p. 484), the analysed rock shows lower K_2O, FeO and Al_2O_3 and higher CaO and MgO. Thus chemically this particular shonkinite falls roughly in between the shonkinite of Basswood type and the shonkinite from Yogo Peak. In the Rogart area it forms a bridging type between the true shonkinite and the mela-syenodiorites. It is therefore suggested that this rock be distinguished by the name shonkinitic mela-syenodiorite.

TABLE /

TABLE V

Shonkinitic mela-syenodiorite, No. 1223, from the basic mass No. 75 east of Corryachvrail.

	Percentages	Mol. Props.
SiO_2	49.56	.8252
Al_2O_3	9.82	.0963
Fe_2O_3	1.96	.0123
FeO	3.37	.0469
MgO	10.03	.2488
CaO	13.42	.2393
Na_2O	2.61	.0421
K_2O	2.06	.0219
H_2O+105°C	1.16	-
H_2O-105°C	.28	-
CO_2	3.94	.0896
TiO_2	1.02	.0128
P_2O_5	.78	.0055
MnO	.16	.0023
	100.17	1.5534 (exclude CO_2)

Normative Composition

Q		0.27
or		12.16
ab		22.07
an		8.98
di	($CaSiO_3$	11.51
	($MgSiO_3$	9.07
	($FeSiO_3$	1.15
hy	($MgSiO_3$	15.90
	($FeSiO_3$	2.03
mt		2.85
il		1.94
ap		1.85
cc		8.96
water		1.44
		100.16

Mode

Orthoclase	10.08
Oligoclase	22.00
Diopside	46.03
Biotite	14.06
Hornblende	1.36
Apatite	1.46
Sphene	0.20
Calcite	4.25
Iron oxides &c.	0.51
	99.95

Analyst: W.H. Herdsman

von Wolff Values

Q = −6.31
L = 41.28
M = 65.02

(ii) Mela-syenodiorites.

The mela-syenodiorites are characterised by a great variability in their texture and in the distribution and relative abundance of their component ferromagnesian minerals. The average rock contains from 50 to 70 per cent of hornblende, biotite and pyroxene in variable proportions. Some of the rocks have pyroxene dominant over biotite and hornblende; others contain both biotite and pyroxene in excess of hornblende, whilst others again may have biotite, pyroxene and hornblende in roughly equal amounts; and still others hornblende in excess of biotite and pyroxene. The mela-syenodiorite differs from the shonkinite in that plagioclase (oligoclase) is the predominant feldspar; orthoclase, however, always forms more than 5% of the rock.

The pyroxene-rich varieties of mela-syenodiorite (Fig. 31) will first be described, as examplified by specimens from the northern margin of the basic mass No. 78, north of Ardaidh Chonachair, and from the western portion of the basic mass No. 10 which outcrops at the summit of Cnoc Bad a' Chrasgaidh. In hand specimen these rocks have a very distinctive greyish green colour due to the presence of closely packed pyroxene crystals in a feldspathic groundmass. The feldspar usually forms large poikiloblastic crystals that break readily along their cleavage planes, which are lustre mottled with inclusions of pyroxene. Black biotite /

biotite flakes, about 5 mm. in diameter, and prisms of hornblende usually form clusters.

In thin sections (313a, 513, 1015, 1025, 1125, 1225) the pyroxene-rich mela-syenodiorites are seen to be composed essentially of pyroxene, feldspar, biotite and hornblende. The pyroxene, which forms the most abundant melanocratic component, is diopside which varies from pale green to colourless and has an extinction angle of about 38°. It builds well-shaped crystals which are enclosed within large plates of feldspar as in the shonkinites previously described. The mela-syenodiorite differs from the shonkinites, however, in that plagioclase is preponderant over orthoclase. It occurs in large broad tabular forms which enclose all the other constituents (Fig. 32). The plagioclase usually exhibits very fine albite twin-lamallae, but it is sometimes untwinned; and whereas oligoclase, An_{24}, is the most common variety, it may be more sodic and locally it varies up to albite. Orthoclase occurs around the margin of the plagioclase, the junction between the two minerals being very irregular. Biotite, with X = straw yellow, Y = Z = brown, is present as large flakes, and hornblende usually forms large poikiloblastic individuals sieved with feldspar (Fig. 33), apatite, biotite and pyroxene. The diopside inclusions within the hornblende commonly exhibit the same optical orientation as the diopside outside but adjacent /

adjacent to the hornblende. Brown sphene, in euhedral crystals and stout prisms of apatite form very conspicuous accessories, other accessories being orthite, zircon, and iron oxides.

The analysis, norm, and mode of a specimen of diopside-rich mela-syenodiorite, No. 1125, from the northern margin of the basic mass No. 63, north of Ardaidh Chonachair are tabulated in Table VI. The analysis shows the rock to be richer in soda than potash and have a very low content of alumina relative to silica. It falls into the subrang of Kilauose (III, '5, 2(3), 4) of the C.I.P.W. Quantitative Classification, in which Kauiite quoted by Johannsen as a typical example of mela-syenodiorite, also falls. The analysis of the diopside-rich mela-syenodiorite, however, is not exactly comparable with any other rock analyses in Washington's Tables.

TABLE /

TABLE VI.

Diopside-rich Mela-syenodiorite No. 1125 from the northern mmrgin of the basic mass No. 78 north of Ardaidh Chonachair.

	Percentages	Mol. Props.
SiO_2	53.49	.8906
Al_2O_3	9.57	.0939
Fe_2O_3	1.78	.0112
FeO	4.33	.0603
MgO	11.54	.2862
CaO	11,76	.2097
Na_2O	2.88	.0465
K_2O	1.16	.0123
H_2O+105°C	.85	-
H_2O-105°C	.15	-
CO_2	Nil	-
TiO_2	1.52	.0190
P_2O_5	.44	.0031
MnO	.21	.0030
	99.68	1.6348

Analyst: W.H. Herdsman

Normative Composition

Or		6.84
ab		24.27
an		9.75
di	($CaSiO_3$	19.08
	($MgSiO_3$	14.79
	($FeSiO_3$	2.24
hy	($MgSiO_3$	11.06
	($FeSiO_3$	1.69
ol	(Mg_2SiO_4	2.03
	(Fe_2SiO_4	.32
mt		2.69
il		2.88
ap		1.04
water		1.00
		99.68

Mode

Oligoclase	27.91
Orthoclase	5.79
Diopside	55.87
Biotite	4.21
Hornblende	2.99
Apatite	1.13
Sphene	.14
Orthite, zircon &c.	.61
	99.65

von Wolff Values

Q = −1.40
L = 37.32
M = 64.12

<u>The biotite-rich mela-syenodiorites</u> are characterised by the diversity of their structures, some of the group being massive whilst the others have a foliated appearance. The massive variety is coarse grained with flakes of dark brownish biotite evenly distributed through the rock. The foliated appearance of the other variety, which occurs in the masses Nos. 74 and 75, near Loch Airidhe Mhòr and Corryachvrail, is due to the parallel orientation of the biotite flakes (323, 922, 2322). Other varieties exhibit patches of hornblende associated with feldspar in a groundmass of the same minerals. There are also varieties which are relatively coarser grained and richer in ferromagnesian minerals than the ordinary types.

In thin sections (19, 113, 323, 425, 523, 614, 823, 92 1523, 1623, 1923, 2023, 2222, 2223, 2322) the rocks are seen to be composed chiefly of grains and prisms of pyroxene, flakes of biotite and some hornblende, together with anhedral crystals of slightly sericitised oligoclase and subordinary orthoclase (Figs. 34, 35 and 37). Apatite and sphene are very abundant, other accessories being calcite, orthite, chlorite, zircon and iron oxides (Fig. 36). The pyroxene is a pale greenish diopsidic variety with a dusty coating of obscure brownish aggregates along the cleavages. It exhibits various stages of transformation to hornblende. The hornblende is found along the /

the cleavages and around the margins of the pyroxenes and increase in amount until finally only relics of pyroxene remain as inclusions within the hornblende. Isolated relics of pyroxene within the hornblende are optically continuous, the traces of the prismatic cleavages of the two minerals, as seen in vertical section, being parallel. The hornblende commonly forms skeletal growths that are sieved with feldspar, apatite, sphene, and pyroxene. It also commonly has isolated, but usually optically continuous, biotite flakes intergrown along its cleavages. It has a pleochroic scheme of X = yellow $<$ Y = green $<$ Z = bluish green. The biotite, which is pleochroic from X = yellow to Y = Z = dark brown to nearly opaque, occurs as large flakes. It also occurs as small flecks intimately associated with both pyroxene and hornblende.

The plagioclase is mostly oligoclase, An_{25}, but it may vary through sodic oligoclase to albite. It occurs as large subhedral crystals that often show albite twinning, and also as small tabular forms enclosed within orthoclase. Orthoclase is often found on the margin of the plagioclase and sometimes extends in tongues along certain crystallographic directions (010, 100, 110) throughout the whole crystals so as to produce an antiperthitic pattern (19. Figs. 38, 39 and 40). The orthoclase of the antiperthitic areas commonly has the same optical /

optical orientation as the orthoclase that is found outside the marginal part of the plagioclase (Figs. 39 and 40). The newly developed orthoclase often contains microperthitic lamellae of untwinned albite (2222, Fig. 41). Both plagioclase and orthoclase show a poikilitic texture, the feldspars tending to enclose the other constituents of the rock. Where orthoclase adjoins the biotite the latter mineral commonly has a saw-like margin (Fig. 41), which might suggest that it has been to some extent replaced by orthoclase.

Amongst the accessory minerals apatite preponderates over sphene, and occurs both as stout prisms and as long needles which may reach 1. 5 mm. in length. The sphene, usually in large euhedral crystals, is pleochroic from pale pinkish yellow to pinkish brown. Calcite is often associated with the sphene and both these minerals appear to be by-products of the alteration of the pyroxene, since the calcite, sometimes together with the associated sphene, usually retains the original shape of the pyroxene. When calcite comes in contact with biotite, the latter shows corroded border along which there is an accumulation of black iron-oxides. The iron oxides also extend along the cleavage of the biotite.

A more basic variety of the biotite-rich mela-syenodiorite (20, 22) resembles the rock just described, but differs from the latter not only in the greater abundance of cafemic minerals /

minerals but also in the fact that the hornblende and biotite are much larger in size. In this rock biotite forms large plates that enclose grains and prisms of pyroxene and anhedral crystals of hornblende (Fig. 42). The feldspar, which may form from 10½ to 20% of the rock, is mainly perthitic orthoclase; it forms very large poikilitic crystals that enclose the other dark constituents. This highly basic variety of biotite-rich mela-syenodiorite shows transitions to the more feldspathic types just described. In its high proportion of orthoclase relative to the plagioclase it also shows some approach towards the shonkinites. It differs from the shonkinites, however, in having hornblende as a conspicuous constituent.

The analysis, norm and mode of a typical example of biotite-rich mela-syenodiorite, No. 614, from the middle of the basic mass No. 79, east of Creag na Pairce, is recorded in Table VII. As compared with the diopside-rich mela-syenodiorite the rock is less rich in MgO and CaO, and richer in total alkalies, K_2O is considerably higher than in the diopside-rich mela-syenodiorite, and equals Na_2O in amount. The rock falls into the subrang Kentallenose (III, 5, (2)3, 3 (4) to which some varieties of lamprophyre and kentallenite belong. The analysis of the biotite-rich mela-syenodiorite, however, is not exactly comparable with any other rock analyses in Washington's Table.

TABLE VII

Biotite-rich Mela-syenodiorite No. 614 from the middle portion of the basic mass No. 79 east of Creag na Pairce.

	Percentages	Mol. Props.
SiO_2	52.38	.8721
Al_2O_3	12.37	.1214
Fe_2O_3	1.21	.0076
FeO	4.58	.0638
MgO	10.86	.2694
CaO	8.26	.1473
Na_2O	2.77	.0447
K_2O	2.73	.0290
H_2O+105°C	1.76	-
H_2O-105°C	.24	-
CO_2	1.02	.0232
TiO_2	1.40	.0175
P_2O_5	.25	.0018
MnO	.23	.0032
	100.06	1.5778 (without CO_2)

Analyst: W.H. Herdsman

Normative Composition

or		16.14
ab		23.43
an		13.26
di	($CaSiO_3$	8.18
	($MgSiO_3$	6.12
	($FeSiO_3$	1.24
hy	($MgSiO_3$	12.73
	($FeSiO_3$	2.62
ol	(Mg_2SiO_4	5.74
	(Fe_2SiO_4	1.31
mt		1.69
il		2.65
ap		.60
cc		2.32
water		2.00
		100.03

Mode

Oligoclase	28.50
Orthoclase	8.06
Biotite	22.48
Hornblende	11.57
Diopside	24.48
Sphene	0.44
Apatite	1.67
Calcite	1.92
Chlorite, Ores	0.94
	100.06

von Wolff Values

Q = −4.72
L = 49.44
M = 55.26

(c) Feldspathic Hornblendite

The feldspathic hornblendite from the south-western corner of the basic mass No. 79, east of Creag na Pairce is a very coarse grained greenish black rock characterised by closely packed prisms of hornblende which have a squarish vertical section measuring as much as 1 or 1.5 cms. across. The hornblende prisms have a random orientation and exhibit lustre-mottling due to the presence of minute inclusions of flecks of biotite and pyroxene that interrupt the reflection from the cleavage surfaces. The interstitial spaces between the hornblende prisms are filled with greenish pyroxene and pinkish feldspars. With decrease in the amount of the feldspathic constituents the rock grades locally into true hornblendite. Hornblendite is also found as small rims around basic inclusions and as residual basic clots (Figs. 6 and 7).

In thin sections (3, 1214) the feldspathic hornblendite is seen to consist dominantly of large prisms of common green hornblende and flakes of biotite, the interspaces between the latter minerals being occupied by anhedral plagioclase that encloses small pyroxene prisms. Accessories are apatite, calcite, sphene, epidote, chlorite and iron-oxide, of which apatite is relatively abundant and calcite is common. Hornblende has X = yellowish green $<$ Y = green $<$ Z = green sometimes with a bluish /

bluish tinge. It builds large prisms and is somewhat sieved around the margins, which are shot through by abundant flakes of biotite, extending not only along the cleavages but also in other directions. There are also inclusions of apatite and sieve-like inclusions of plagioclase and granular pyroxene. The inclusions of pyroxene are usually surrounded and separated from the main hornblende by patches of light greenish amphibole. This amphibole has X = nearly colourless $<$ Y = pale bluish green $<$ Z = green and has a smaller extinction angle ($Z \wedge C = 13^{\circ}$ to 20°) than the ordinary green hornblende. It is a member of the actinolite-tremolite series, which also occurs in the interstitial areas between the large hornblende prisms, in close association with the pyroxene crystals (Figs. 43, 44 and 45). It seems likely that the large prismatic hornblende has formed partly as a replacement of pyroxene, and that the actinolitic variety is chemically an intermediate stage between the pyroxene and the replacing green hornblende. The actinolitic amphibole, apart from its somewhat fibrous habit in this rock, resembles the light coloured amphibole in the altered hornblendic Moine rocks (1, 125, 3014).

The plagioclase commonly has a sericitised central portion, oligoclase, An_{24}, surrounded by a clear and more sodic variety. Orthoclase is present in very subordinate amount.

The /

The chemical analysis, norm and mode of the feldspathic hornblendite, No. 1214, are recorded in Table VIII. The rock is characterised by low silica and alumina, and high MgO. K_2O and Na_2O are present in about equal amounts. The rock falls into the subrang Rossweinose (''IV, 1", 3, 2 "2). Compared with the rocks of Ach'uaine type (No. 1223, Table V; No. 1125, Table VI; No. 614, Table VII), the most significant changes are the marked increase in MgO and total FeO with a corresponding decrease in Al_2O_3 and total alkalies.

TABLE /

TABLE VIII

Feldspathic Hornblendite No. 1214 from the south-western margin of the basic mass No. 79 east of Creag na Pairce.

	Percentages	Mol. Props.
SiO_2	48.94	.8149
Al_2O_3	7.66	.0751
Fe_2O_3	2.68	.0168
FeO	5.84	.0813
MgO	17.81	.4417
CaO	10.25	.1828
Na_2O	1.87	.0302
K_2O	1.68	.0178
H_2O+105°C	1.43	-
H_2O-105°C	.18	-
CO_2	Nil	-
TiO_2	.72	.0090
P_2O_5	.46	.0032
MnO	.33	.0047
	99.85	1.6775

Analyst: W.H. Herdsman

Normative Composition

or		9.91
ab		15.83
an		7.54
di	($CaSiO_3$	16.85
	($MgSiO_3$	12.82
	($FeSiO_3$	2.29
hy	($MgSiO_3$	.72
	($FeSiO_3$	.13
ol	(Mg_2SiO_4	21.58
	(Fe_2SiO_4	4.26
mt		3.89
il		1.37
ap		1.08
water		1.61
		99.88

Mode

Feldspar	14.09
Biotite	12.41
Hornblende (incl. small amt. Tremolite)	53.79
Diopside	17.79
Apatite	1.35
Orthite, Ore	.54
	99.97

von Wolff Values

Q = -10.83
L = 29.36
M = 81.48

4. The Granitisation Series

(a) Appinites

The term appinite is used in this paper strictly in accordance with Bailey's (1916) original definition: "The appinites, named after the local parish of Appin, are the plutonic equivalents of the hornblende vogesites and spessartites; they are dark rocks of medium to coarse texture, and mainly composed of green or brown hornblende (either stumpy or acicular) in a groundmass which contains plagioclase, orthoclase and quartz in variable proportions; granophyric growths of quartz and orthoclase are common; where plagioclase is the dominant felspar, quartz may be almost or quite absent; olivine (as pseudomorphs), augite, and biotite are sometimes present; apatite is a conspicuous accessory". The term appinite thus includes the "basic hornblendic varieties of both syenites and diorites" (1916, pp. 167-168).

In 1932 MacGregor and Kennedy extended the term appinite to a suite of rocks that is equivalent to the whole series of the basic rocks of Ach'uaine type. They stated that "The group as a whole is characterised by the presence of quartz and alkali-feldspar in rocks of all degrees of basicity. In the basic rocks the characteristic ferromagnesian minerals are /

are green hornblende and pale pyroxene. A feature of considerable importance (p. 119) is the essential identity of this rock series with the 'Hybrid Rocks of Ach'uaine Type' described by Professor H.H. Read from Sutherland" (1932, p. 107).

As is shown in this thesis, the 'Hybrid Rocks of Ach'uaine Type' include shonkinites, shonkinitic mela-syenodiorites, mela-syenodiorites and hornblendites, in addition to appinites as originally defined by Bailey. The extension of the term appinit to include so wide a range of rocks would obviously detract from its usefulness. Moreover, such an extension of the term is undesirable from a petrogenetic standpoint, for, whereas the hornblendites, shonkinites and mela-syenodiorites have developed from the hornblendic rocks of Moine type as basic fronts of granitisation, the appinites represent a stage in the subsequent granitisation of the rocks of the basic front.

The rocks here described were collected from the basic mass No. 79, east of Creag na Pairce where the appinites are well exposed both in the river bed of Torbreck Burn and at the norther margin of the mass. Similar rocks have also been found in the basic mass No. 73 north of Loch Airidhe Bheg (8, 420, 424, 524, 1524, 1624, 3120) and in the basic masses Nos. 14, 71, 72, 74, 75, 78 &c. (723, 1325, 1525, 1625, 1722, 2522, 3222).

In hand specimen the appinites are seen to be composed of abundant squat prisms of hornblende that have a roughly squar vertical /

vertical section, averaging about 2 or 3 mm. across, embedded in a pinkish base of feldspar, which may occasionally be diversified by patches of greenish pyroxene. The rock sometimes contains hornblende as the only mafic mineral; it might be then called a basic hornblende-diorite (4). Some of the appinites (9, 3012) are coarser grained and contain more elongated prisms of hornblende that range in size from 10 x 20 mm. up to 15 x 20 mm.

In thin sections (4, 6, 2214, 2314) it is seen that hornblende forms nearly one-half of the rock, the remainder being composed of feldspar, biotite and pyroxene, together with accessory amounts of sphene, apatite, quartz, orthite, chlorite and iron oxides. Hornblende has X = pale yellowish green $<$ Y = green with brownish tinge $<$ Z = green with bluish tinge, and $Z \wedge C$ = ca 24°. It is usually poikiloblastic or even highly skeletal, being sieved with feldspar and enclosing in addition apatite needles, sphene, orthite, pyroxene grains and numerous flakes of biotite (Figs. 47 and 48). The biotite is also commonly skeletal in form, and it is often intergrown with the hornblende so that the basal cleavage of the biotite coincides with the prismatic cleavage of the hornblende (Figs. 49 and 50). Less commonly the biotite extends across the prismatic cleavages of the hornblende, or skeletal flakes of biotite appear to weave through /

through the two sets of prismatic cleavage seen in basal sections of hornblende (Fig. 50).

Pyroxene occurs as small irregular grains and as subhedral prisms scattered within the large feldspars. It exhibits various stages of alteration to amphibole. The amphibole in immediate contact with the pyroxene is usually a light coloured member of the tremolite-actinolite series. The latter passes outwards to green hornblende.

Of the feldspars the plagioclase is preponderant over orthoclase and is usually twice as abundant. The plagioclase, oligoclase, An_{27}, is strongly sericitised and is commonly margined by orthoclase. In such an association the contact between the two minerals is very irregular, and the orthoclase commonly contains perthitic lamellae and patches of albite-oligoclase which are physically continuous with the adjoining oligoclase (Figs. 47 and 52). Sphene and apatite form the most important accessories, and of these the sphene is much more abundant than apatite. It occurs as large euhedral and subhedral crystals up to 2 or 3 mm. in size, and as skeletal forms sieved with hornblende, feldspar and apatite. Apatite needles are found throughout the rock. Quartz is scarce and is not represented in some of the slides; when present it occurs as small grains.

Appinite /

Appinite (No. 2314) from the northern margin of the basic mass No. 79 has been analysed, and the results, together with the norm and mode are set out in Table IX.

TABLE /

TABLE IX

Appinite No. 2314 from the northern margin of the basic mass No. 79 east of Creag na Pairce.

	Percentages	Mol. Props.
SiO_2	54.26	.9034
Al_2O_3	10.98	.1077
Fe_2O_3	1.22	.0076
FeO	5.17	.0720
MgO	11.32	.2808
CaO	7.62	.1359
Na_2O	2.74	.0442
K_2O	2.48	.0263
H_2O+105°C	1.95	-
H_2O-105°C	.22	-
CO_2	traces	-
TiO_2	.84	.0105
P_2O_5	.78	.0055
MnO	.13	.0018
	99.71	1.5957

Analyst: W.H. Herdsman

Normative Composition

or		14.63
ab		23.17
an		10.35
di	($CaSiO_3$	9.34
	($MgSiO_3$	6.74
	($FeSiO_3$	1.76
hy	($MgSiO_3$	19.63
	($FeSiO_3$	5.11
ol	(Mg_2SiO_4	1.27
	(Fe_2SiO_4	.37
mt		1.75
il		1.60
ap		1.85
water		2.17
		99.75

Mode

Oligoclase	28.21
Orthoclase	14.48
Biotite	4.39
Hornblende	44.91
Sphene	3.86
Apatite	1.98
Chlorite, ores	2.16
	99.99

von Wolff Values

Q = −1.50
L = 44.68
M = 56.84

(b) Diorites and Quartz-Diorites

This group of rocks commonly occurs as a transitional zone between the appinites and the granodiorites. In hand specimens the diorites and quartz-diorites are pinkish grey rocks containing roughly aligned feldspar crystals about 5 mm. long, with black hornblende prisms streaking around them.

The rock here described was collected from the same exposure in the basic mass No. 79 within the zone of granodiorite as the analysed appinite. In thin section (2414) it is seen to be composed of plagioclase and hornblende together with subordinate orthoclase and biotite; quartz is absent from this slice, but is present in Nos. 116, 136, 266. The accessories are apatite, sphene, chlorite, zircon and iron oxides, of which sphene is most abundant.

The plagioclase, euhedral to subhedral oligoclase, An_{25}, exhibits fine albite lamellae often combined with carlsbad twinning. The crystals usually have sericitised cores and clear margins against the orthoclase (Fig. 53). Between these two minerals there is always a highly irregular sutured and saw-like junction. Within the orthoclase small relict patches of oligoclase that are optically continuous with the adjoining oligoclase still remain. The relics of oligoclase often have a clear rim of more sodic oligoclase or albite where they adjoin the /

the orthoclase. Petaloid forms of myrmekite consisting of oligoclase and vermicular quartz, sometimes protrude into the orthoclase from the margin of residual oligoclase. The orthoclase is microperthitic, the albite lamellae of the microperthite commonly being physically continuous with sodic oligoclase or albite that rims the oligoclase relics (Fig. 54).

The hornblende has X = yellowish green < Y = green < Z = green with a slight bluish tinge. It is often sieved with feldspar and encloses biotite, apatite needles and crystals of sphene.

Sections (116, 136, 266) of the dioritic rocks from the basic masses Nos. 23 and 32 in the zone of migmatites, differ from the example just described in containing abundant biotite and quartz. The biotite, with X = straw yellow, Y = Z = dark brown, is commonly altered to penninite along the cleavages. In these rocks orthoclase is scarce or absent, and the oligoclase sometimes occurs as euhedral tablets arranged in a mosaic pattern.

(c) Granodiorite

The granodiorite is a coarse grained greyish white rock with a foliated appearance due to the rude alignment of the feldspar crystals and to the streaking-out of the dark components. It /

It contains large pinkish crystals of alkali feldspar that usually range up to 1 x 1.5 cm. in size, and have a mottled appearance due to the presence of abundant small inclusions of the dark minerals.

In thin sections (5, 44a, 213, 428, 2514) the constituent minerals are seen to be plagioclase, orthoclase, quartz, biotite and hornblende with accessory apatite, sphene, chlorite, orthite, calcite, monazite and iron oxides. The plagioclase is usually oligoclase, An_{25}, and it is generally euhedral, slightly sericitised and finely twinned. Not infrequently it exhibits sinuous and dentate outlines against the orthoclase around the margin (Figs. 55, 56 and 57). Small petaloid-shaped myrmekite, which consists of oligoclase and vermicular quartz, is often found in the protruding parts of oligoclase where it encroaches upon the orthoclase (Figs. 55 and 59). Myrmekite also appears in small isolated inclusions of oligoclase which occur in orthoclase (Fig. 60). The oligoclase of the myrmekite is nearly always in optical continuity with the oligoclase to which it is attached. The junction between myrmekite and orthoclase is always rather well defined.

Orthoclase is distinctly less abundant than plagioclase and occurs either in anhedral forms around the margin of the plagioclase (Figs. 55, 56 and 57), or as tabular porphyroblastic crystals /

crystals, which are nearly always perthitic and sometimes show carlsbad twinning (Fig. 60). The large orthoclase crystals are generally rimmed with myrmekite and margined by oligoclase (Fig. 60). Small patches of sericitised oligoclase that occur within the orthoclase have clear rims of more sodic oligoclase or even albite, which do not extinguish uniformly with the marginal oligoclase. It is very significant that the wider portions of the perthite lamellae not infrequently show a turbid central portion of sericitised oligoclase (Fig. 58). This feature suggests that the plagioclase lamellae may represent relics of replaced oligoclase individuals. Other minerals included within the large potash feldspar crystals are biotite flakes, quartz blebs and apatite needles. Quartz is not abundant, and is anhedral in form with curved and lobe-shaped margins against the feldspar. Blebs or drops of quartz within the feldspar are in optical continuity with larger quartz individuals outside the feldspar (Fig. 61).

The ferromagnesian minerals are often scattered around the large feldspar individuals. The biotite has X = straw yellow, Y = Z dark brown with a slightly greenish tinge. Along the cleavage cracks it is often partially altered to chlorite associated with separated granules of iron oxides. The hornblende is of the common green variety, with X = greenish yellow /

yellow Y = green with a slightly brownish tinge Z = darker green. It is usually partially altered to chlorite and a greenish yellow material that has not been identified. The relative proportions of biotite and hornblende are variable from specimen to specimen. Sphene forms wedge-shaped crystals, pleochroic from yellowish brown to reddish brown. It is often altered to opaque ores and a brownish material.

The chemical analysis of a typical specimen of granodiorite, collected close to the basic mass No. 79, together with the norm and mode are tabulated in Table X. As compared with the appinites (No. 2314, Table VII) the significant differences are lower cafemic constituents and higher Al_2O_3, K_2O and Na_2O.

TABLE /

TABLE X.

Granodiorite No. 2514 from outside the northern margin of the basic mass No. 79 east of Creag na Pairce, three yards away from the appinites No. 2314.

	Percentages	Mol. Props.
SiO_2	65.36	1.0883
Al_2O_3	16.08	.1577
Fe_2O_3	1.09	.0068
FeO	2.26	.0315
MgO	2.49	.0618
CaO	2.86	.0510
Na_2O	4.22	.0681
K_2O	3.18	.0338
H_2O+105°C	1.13	-
H_2O-105°C	.10	-
CO_2	traces	-
TiO_2	.83	.0104
P_2O_5	.29	.0020
MnO	traces	-
	99.89	1.5114

Normative Composition

Q		18.75
or		18.81
ab		35.70
an		12.28
c		1.17
hy	($MgSiO_3$	6.20
	($FeSiO_3$	1.89
mt		1.57
il		1.58
ap		.67
water		1.23
		99.85

Mode

Quartz	20.92
Oligoclase	42.89
Orthoclase	22.84
Biotite	6.07
Hornblende	3.88
Sphene	0.26
Apatite	0.14
Chlorite, Ore &c.	3.13
	100.13

Analyst: W.H. Herdsman

von Wolff Values

Q = 19.87
L = 67.89
M = 12.34

V. PETROGENESIS OF THE ROCKS OF ACH'UAINE AND APPINITE TYPES.

The hornblendic members, from which the rocks of Ach'uaine and Appinite types were derived, form only a part of the Moine complex that has suffered profound modification during the regional migmatisation and granitisation; hence, the inter-relationship between the hornblendic Moine rocks and the rocks of Ach'uaine and Appinite types, and the modes of origin of these types, can be seen in their proper perspective only by making a survey of the large-scale structure of the Rogart migmatite area as a whole - a survey that involves an enquiry into the origin of the migmatites and the granodiorite.

Firstly, the Rogart migmatite field is characterised by a continuous transition from the rocks of the Moine Series through the zone of migmatites to the zone of granodiorite. In the field, a band of Moine rocks can be traced along the strike through the zone of migmatites into the granodiorite; thus the zone of migmatites is just a transitional element between the two end members, with an increasing degree of migmatisation from the outer to the inner zone. In redrawing the geological map of the area under review (Fig. 1), the rigid boundaries between the three petrological zones that were originally drawn on the Geological Survey 1" Sheet 103, were abandoned. /

abandoned. A glance at the trend lines on the map will suffice to show that the three petrological units are structurally continuous. This structural continuity has been noted by Read, who, dealing with the planar foliation of the granodiorite, wrote: "These directions of dip and strike of the fluxion are in agreement, in the first place with those of the layers of granite in the zone of inclusions, in the second place with those of the bedding of Moine inclusions in this zone, and both these dispositions are in accord with the regional strike and dip of the Moine granulite outside the granite-granulite complex. ..... The fluxion-directions are emphasized by the lie of the dark patches or inclusions in the granodiorite". (1925, p. 23. See Figs. 67-76.

Secondly, the finest details of the original structures of the framework of pre-existing Moine rocks (chiefly siliceous and semi-pelitic rocks) are preserved in the migmatites (Figs. 77-93), and to a certain extent in the granodiorite, as expressed by the planar foliation (Figs. 69-73). The significance of this striking feature has been adequately recognised and expressed by Hugh Miller (Junior) to whom reference has already been made in the early part of this thesis. In his field report (1893) he wrote: "The structures in the granites and granitic gneisses .... are now found to be to a large extent imitation-structures, due to a simulation of the form

and /

and structural features of the country rock (the Eastern Schist) by granites that have by some means crept into their place. ...... In the granites thus produced there is simulated, so far as crystalline matter can do so, the fine layering of some parts of the Eastern Schist, and the coarse banding of the others: there is also preserved in cast the rumplings and striation of their surface, and to some extent also apparently their lines of cleavage ...... the inclusion-structure (as well as the inclusion-planes) everywhere retains the same dip and strike as that of the country rock".

Very shortly afterwards Horne and Greenly (1896) published their masterly account "On foliated granites and their relations to the crystalline schist in Eastern Sutherland". These two pioneers remarked: "With regard to the granites, it is difficult to believe that they are wholly foreign matter" (1896, p. 647). Later, stimulated by Sir W. Roberts-Austen's remarkable experiments on the inter-diffusion of solid metals, Greenly (1903) contributed a paper on "The diffusion of granites into crystalline schists". He first stressed the metamorphic theory of the so-called igneous rocks, and then turned to the application of Roberts-Austen's results to the interpretation of contact phenomena such as are seen in Eastern Sutherland, where granites are observed to pass into the surrounding gneissese rocks /

rocks by perfectly gradual transitions. He stated: (pp. 211-212): "The signular fact that the inclusions of gneiss in granite, even down to the thinnest films, are so very seldom, in these zones, disturbed in position (ibid., fig. 4), affords some support for the view that the extension of the magma proceeded by quiet diffusion rather than by forcible injection". and "The experiments quoted lead us to expect that diffusion might go on even after solidification .... Indeed, what we know of the changes that have certainly gone on in solid rocks shows that the solid state is no obstacle to extensive molecular change". Indeed no geologist could visit these localities without being convinced that the processes of migmatisation and granitisation have taken place in a solid medium. The phenomena, which are conspicuously exhibited, admit of only one explanation; that the migmatites and granodiorites are the successive witnesses of advancing waves ('fronts') of migrating materials which passed through the Moine rocks while the latter themselves remained essentially solid.

It should perhaps be emphasized here that, although the above quoted statements were of such early dates, they approach the modern position astonishingly closely. Much detailed work has been done since those pioneering days. Notable, for example, are the systematic regional and petrological accounts /

accounts of various migmatite areas in the Northern Highlands by Read (1925, 1931) and the more recent contributions by Y.C. Cheng (1942, 1944) whose work was mainly concerned with mineralogical and petrological details. Unfortunately, the idea that migmatites have resulted from injection or soaking of granitic or trondhjemitic 'juice' has been held so strongly and persistently by these later workers that the development of the conception of migmatisation and granitisation in this area was undoubtedly retarded.

Despite Cheng's advocacy of the view that the migmatites and granites of the Bettyhill area were formed by intense soaking of pre-existing Moine rocks by circulating fluids, he has nevertheless, by his careful and elaborate accounts of the detailed sequence of mineralogical changes, given us a nucleus of sound knowledge towards the understanding of the formation of migmatites. From an examination of a series of strike-wise set specimens, he showed that the change from pelitic gneiss to permeation-gneiss is essentially in the nature of feldspathisation, with enrichment of oligoclase in the latter. In a comparative study of the chemical analyses of a normal pelitic gneiss and of two permeation-gneisses from the same band, he demonstrated that, proceeding from the normal pelitic sediment to the modified rocks, si, fm, c and k decrease, while al, alk, and /

and mg rise, and that the Na_2O/K_2O ratio increases to more than 1.27. From these data he concluded: "The permeation-gneiss might have been produced from the original sediment by the gain of soda, alumina and a little magnesia and the loss of silica and a little iron oxide, lime and potash" (1944, p. 123).

The semi-pelitic granulites give rise to three differen series of migmatites. The first type is fine migmatite. Comparison between the respective amounts of Na_2O, K_2O and CaO, calculated from the mineral compositions of a series of rocks, shows that: "Proceeding from less migmatised rock to migmatitic granite, Na_2O increases rapidly, K_2O decreases gently while CaO increases by a trifling amount" (1944, p. 129). The total chemical changes involved, as deduced from the mineralogical transformations, are the introduction of Na_2O, Al_2O_3 and CaO with the concomitant driving out of K_2O, MgO, FeO and H_2O (see 1944, p. 129, Fig. 6).

The second type is augen migmatites, in which potash-feldspar augen have been metasomatically formed at the expense of the pre-existing minerals. Cheng attributed the formation of potash feldspar to the action of potash-bearing fluids. As to the origin of this potash, he remarked: "It may be reiterated that in the formation of the augen, part of the potash needed to form their orthoclase is possibly provided during the production of /

of pelitic permeation gneiss and the rocks of the fine semi-pelitic migmatite series". (1944, p. 130).

Siliceous granulites and hornblendic rocks are considered by Cheng as being more resistant to the migmatitic changes. He regarded the modification of most of the siliceous granulites as having resulted "from the recrystallisation of original siliceous rocks in the presence of abundant volatile fluids which only serve as a medium for the operation and do not affect the chemical composition of the rock" (1944, p. 132). When they <u>are</u> changed, increase in soda seems to be the more prominent.

The hornblende-schist of Durcha Type is occasionally converted into biotite-chlorite schist. The chemical change involved in such a process, as deduced from the mineralogical evidences involves at least an introduction of K_2O (see 1944, p. 134, Fig. 9). With regard to this potash he remarked: "It is interesting to note that while these thin bands have been modified by potash-rich fluids and later hydrothermal solutions, the associated semi-pelitic granulites are changed by the granitic liquor, the dominant effect of which is sodic in character" (1944, p. 134).

In the summary of the changes in the Moine rock types, Cheng emphasized "that the production of the permeation-gneiss not /

not only involves the addition but also the subtraction of material; thus the changes are essentially of the nature of metasomatism, and such a conclusion probably holds for all the migmatitic rocks" (1944, p. 143). As we can see from the above outline, apart from the correlation of part of the potash, the destiny of most of the subtracted materials, including Fe, Mg and H_2O, is left still remaining a mystery. Moreover, there has been a tendency by Cheng, as well as by earlier geologists, to concentrate attention on migmatisation and granitisation in a one-sided manner, i.e. on rocks approaching the composition of granite, while leaving the development of associated basic and ultra-basic rocks without comment, and their petrogenetic significance without discussion or explanation.

The association of basification of the peripheral sediments with the development and upward progress of the migmatites in orogenic belts has not, however, escaped the notice of geologists who have worked in Fennoscandia and Greenland. In 1935 Wegmann observed the enrichment of both leptites and sedimentary rocks in cordierite, garnet and biotite, in the peripheral zones of the migmatite regions. He correlated this Fe-Mg enrichment with the loss of Fe and Mg from the migmatised rocks and believed the transformation concerned to have been accomplished as a result of migrations of material through the intergranular films. At about the same time Backlund also observed the same phenomena; he /

he further emphasized the complicated chemical interchanges during the process of migmatisation and granitisation, and pointed out that materials emigrating out of one specific rock type in the migmatite-assemblage may form the incoming material fixed in some of the other rock varieties. For example, as a result of his study of the successive changes during the migmatisation of limestones (1936a), he found that the initial stage of the migmatisation of limestone is characterised by fixation of Fe, Mg and Si, with concomitant driving out of Ca and CO_2. Reference may also be made to his study of the conversion of basaltic rocks and associated tuffs to eclogites through the following transformation series (1936b):

Basalt ⟶ uralite-porphyrite ⟶ greenstone ⟶ amphibolite ⟶ garnet-amphibolite

and the successive changes at any of these stages to skarn (1943). Thus, he has shown that the results of migmatisation and granitisation are not always granitic-looking rocks: some of the rock products become more basic. He correlated the enrichment of cafemic constituents, both in the basic rocks within the migmatite field and in the sediments of the frontal zone of the migmatites, with the progressive removal of Fe, Mg and Ca from the granitised regions. He concludes that granitisation is caused by successive replacements with complementary displacements and migrations of chemical elements within the solid state. He regards this process /

process of diffusion in the solid as one of migration of ions by way of structural faults, deformations and discontinuities in crystal lattices, full advantage being taken of potential differences of lattice energies.

Such correlation of granitisation and basification has provided the stimulant for a reorientation of views concerning the rocks of the Rogart migmatite area. A comparison of the geological setting of the Rogart area with the outline just presented of the migmatites of the Bettyhill area makes it evident that the pre-existing Moine framework of the migmatites is essentially the same in both areas. In the Rogart area the semi-pelitic, pelitic and siliceous members of the Moine Series have all been altered to corresponding types of migmatites; but what has happened to the hornblendic rocks?

The hornblendic rocks of both sedimentary and igneous origin of the Moine Series are relatively resistant to the migmatitic changes; they represent local centres of strong chemical contrast with the surrounding rocks and of high lattice energy. Thus, in consequence, they have not kept pace with the general changes suffered by the surrounding rocks; instead, they become the repositories for the cafemic constituents displaced from other members of the Moine Series which are undergoing granitisation and therefore they tend to become more basic.

It /

It is thus evident that the changes in both the hornblendic and other members of the Moine Series are closely related.

The rocks of Ach'uaine type can be satisfactorily interpreted only as the basification products of the hornblendic Moine rocks, resulting from the fixation of cafemic constituents and K displaced from associated rocks undergoing migmatisation and granitisation. Subsequently, as rocks of Ach'uaine type in turn became granitised, they evolved through appinites, diorites and granodiorite. The cafemic constituents displaced during these changes were once again driven forward to the frontal zone of granitisation where they are not fixed within hornblendite rims margining pseudo inclusions. This conclusion is based on the following independent lines of evidence.

A. <u>The critical field evidences are</u>:

(a) The field occurrences of the basic masses of Ach'uaine type in the zone of migmatites and granodiorite closely correspond to the hornblendic bodies in the Moine of both sedimentary and igneous origin.

(b) The general increasing variability of the rock types in the basic masses of Ach'uaine type from the outer to inner zone of migmatites and in the granodiorite indicates that the formation of the basic rocks is closely related to the processes of migmatisation and granitisation.

(c) Relics of hornblendic rocks have been found in the basic masses of Ach'uaine type. The relict hornblendic patches show the original character of the pre-existing Moine rocks, and the foliation agrees with the foliation of the neighbouring /

neighbouring Moine granulites. In the granodiorite the trend of the basic bodies and the relict foliated structure agree with the planar foliation of the granodiorite.

(d) Within the basic masses the relict hornblendic rocks constitute the following gradational series:

Relict hornblendic Moine rocks ⟶ relict hornblendic rock with pyroxene patches ⟶ rocks of Ach'uaine type including shonkinite and mela-syenodiorites ⟶ hornblendite and feldspathic hornblendite ⟶ appinite ⟶ diorite and quartz-diorite ⟶ granodiorite.

(e) In the early stages of alteration of the hornblendic Moine rocks, the original foliation may still be preserved in the basic rocks, as examplified by the pyroxene-biotite-hornblende-schists.

(f) The development of agmatite in some of the basic masses in the zone of migmatites. The fragmentary inclusions in the agmatites give an evolutionary sequence from hornblende-biotite-pyroxene-schist (basified schist) through hornblendite to more or less granitic-looking rocks and granodiorite.

B. <u>The significant petrological, mineralogical and textural evidences are</u>:

(a) The microscopical gradation from the indisputable hornblendic Moine rocks, through shonkinite, mela-syenodiorite, hornblendite and feldspathic hornblendite, appinites and diorites to granodiorite.

(b) The replacement habit of many minerals, as examplified among the melanocratic minerals by the relation of diopside to hornblende, and the replacement series from diopside to green hornblende through actinolite-tremolite varieties.

Among the leucocratic minerals the relationship between the potash feldspar and plagioclase follows the trend:

Sodic /

Sodic-andesine or basic oligoclase ⟶ sodic-oligoclase or albite (± antiperthite) ⟶ orthoclase (± perthite and myrmekite).

(c) The presence of highly poikiloblastic and skeletal texture in biotite, hornblende, diopside, feldspar, and sphene suggests growth in a solid medium.

(d) The development of myrmekite.

(e) The sutured outlines of quartz where it adjoins the feldspar.

(f) The abnormally high content of apatite and sphene in the basic rocks.

Finally, in view (a) of the fact that there is no sign of the Rogart granodiorite having once been magmatic and (b) of the field and petrological evidences found during the present investigation, the 'hybridisation' hypothesis formerly advocated by Read (1925, 1926, 1931) as to the origin of the rocks of Ach'uaine type, must be discarded.

VI. GEOCHEMISTRY

1. Rocks of Ach'uaine and Appinite Types in the Zone of Migmatites and Granodiorite.

As outlined in Section III, 1, p. 53 of this thesis, the complete sequence of changes exhibited by the hornblendic rocks of Moine Type within the zone of migmatites and the zone of granodiorite is as follows:

← Basification Series →

Hornblendic Moine Rocks No. 1330 → Relict Hornblendic Rocks Nos. 3014 & 313 → Shonkinitic mela-syenodiorite No. 1223 → Feldspathi[c] Hornblendi[te] No. 1214

Relict Hornblendic Rocks Nos. 3014 & 313 → Mela-syenodiorites Nos. 1125 & 614 → Feldspathi[c] Hornblendi[te] No. 1214

← Granitisation Series →

Feldspathic Hornblendite No. 1214 → Appinites No. 2314 → Diorites → Granodiorite No. 2514

In order to elucidate the successive chemical changes involved in this sequence of transformations, the nine new chemical analyses are repeated in their petrological and field order in Table XI. The three items (Nos. 1223, 1125, and 614) of the rocks of Ach'uaine type may be in part of simultaneous formation, with biotite-rich mela-syenodiorite, No. 614, the most common type, and probably have a longer time-range of formation than the other two. A variation diagram, Fig. 9 , has been /

been constructed with the analyses of the different rock members plotted at equal intervals according to their petrogenetic order.

TABLE /

TABLE XI

	No. 1330	No. 3014	No. 313	No. 1223	No. 1125	No. 614	No. 1214	No. 2314	No. 2514
SiO_2	51.88	56.92	54.86	49.56	53.49	52.38	48.94	54.26	65.36
Al_2O_3	17.24	9.16	5.47	9.82	9.57	12.37	7.66	10.98	16.08
Fe_2O	3.46	1.02	1.67	1.96	1.78	1.21	2.68	1.22	1.09
FeO	5.70	3.93	5.18	3.37	4.33	4.58	5.84	5.17	2.26
MgO	5.58	12.58	11.44	10.03	11.54	10.86	17.81	11.32	2.49
CaO	8.22	9.15	13.48	13.42	11.76	8.26	10.25	7.62	2.86
Na_2O	3.06	3.32	1.02	2.61	2.88	2.77	1.87	2.74	4.22
K_2O	2.21	.64	.91	2.06	1.16	2.73	1.68	2.48	3.18
H_2O+105°C	1.42	1.19	.92	1.16	.85	1.76	1.43	1.95	1.13
H_2O-105°C	.19	.08	.30	.28	.15	.24	.18	.22	.10
TiO_2	.91	.46	.34	1.02	1.52	1.40	.72	.84	.83
P_2O	.08	.09	2.92	.78	.44	.25	.46	.78	.29
MnO	.14	.12	.19	.16	.21	.23	.33	.13	Traces
CO_2	Nil	1.42	.98	3.94	Nil	1.02	Nil	Traces	Traces
	100.09	100.08	99.68	100.17	99.68	100.06	99.85	99.71	99.89

No. 1330. Hornblende-schist, Hornblendic Mass on top of Creag Dail na Méine (Table I)

No. 3014. Relict hornblendic rocks, Basic Mass No. 79 (Table III)

No. 313. Relict hornblendic rock with pyroxene patches, Basic Mass No. 10 (Table IV)

No. 1223. Shonkinitic mela-syenodiorite, Basic Mass No. 75 (Table V)

No. 1125. Diopside-rich mela-syenodiorite, Basic Mass No. 78 (Table VI)

No. 614. Biotite-rich mela-syenodiorite, Basic Mass No. 79 (Table VII)

No. 1214. Feldspathic hornblendite, Basic Mass No. 79 (Table VIII)

No. 2314. Appinite, Basic Mass No. 79 (Table IX)

No. 2514. Granodiorite, outside Basic Mass No. 79 (Table X)

An examination of the above tabulated outline of the rock sequence together with the variation diagram leads to the following considerations:

(1) The initial stage of migmatisation and granitisation of the hornblendic Moine rocks found within the zone of migmatites and granodiorite, as represented by the relict hornblendic rock No. 3014, and the relict hornblendic rocks with pyroxene patches No. 313, is characterised by a marked decrease of Al_2O_3, alkalies, and total FeO. The decrease of Al_2O_3 is progressive and drastic. K_2O decreases markedly to No. 3014, after which it comes in again in a minor scale. Na_2O increases slightly in No. 3014 and decreases again in No. 313. The constituents that have increased are MgO, CaO, SiO_2, P_2O_5 and MnO. MgO shows a marked culmination in No. 3014, after which it decreases slightly. CaO increases progressively and shows marked culmination in No. 313. The sum of FeO, MgO and CaO increases progressively and shows a marked culmination in No. 313. As to the minor constituents: TiO_2 decreases progressively from No. 1330 to No. 313, whilst P_2O_5 shows a very marked culmination in No. 313, and MnO also increases in No. 313. Thus taking this series as a whole, it is essentially one of basification with subordinate silication. In accordance with such a change, the relict hornblendic /

hornblendic Moine rocks show geochemical culmination of MgO, CaO (total FeO + MgO + CaO), SiO_2, P_2O_5 and MnO.

The feldspathic constituents (other than SiO_2), especially the Al_2O_3, are driven out from this zone of basification. These displaced constituents might be expected to be fixed in the surrounding Moine rocks and their migmatitic derivatives. This seems to be confirmed by Cheng's findings in Bettyhill area (1944), where the migmatisation of most of the Moine country rocks, including even the pelitic types, involved the introduction and fixation of Al_2O_3.

(2) The further change from the relict hornblendic rocks to rocks of Ach'uaine type (Shonkinitic [Mela-syenodiorite] No. 1223) mela-syenodioritites Nos. 1125 and 614) is characterised as a whole by decrease of SiO_2 and MgO FeO and by the complementary increase of Al_2O_3 and total alkalies. SiO_2 shows marked geochemical depression in No. 1223, after which it comes in again on a small scale. CaO remains high in No. 1223, after which it decreases progressively from No. 1223 to No. 614. The increase of Al_2O_3 is progressive, which is probably in accordance with the development of biotite in the shonkinitic [Mela-syenodiorite] and biotite-rich mela-syenodiorites. Na_2O increases throughout the series, whilst K_2O shows a similar increment, except for a slight break from No. 1223 to No. 1125. MgO and total FeO fluctuate /

fluctuate slightly, but probably decrease slightly on the whole The sum of FeO, MgO and CaO decreases. P_2O_5 decreases progressively, while MnO and TiO_2 increase markedly, and the latter shows culmination in No. 1125. Thus the desilication change from the relict hornblendic rocks to rocks of Ach'uaine type is predominantly one of feldspathisation.

(3) The hornblendite and feldspathic hornblendite which are developed locally in association with the rocks of Ach'uaine type where the latter are themselves granitised and converted to appinite, diorite and granodiorite, are characterised by the culmination of all the cafemic constituents and together with an increase of P_2O_5 and MnO, and by the complementary decrease of SiO_2, Al_2O_3 and total alkalies. TiO_2 also decreases in No. 1214. Thus the development of feldspathic hornblendite from the rocks of Ach'uaine type represent the still further basification of what was originally hornblendic Moine rocks.

(4) The subsequent granitisation series as examplified through the appinite No. 2314, to granodiorite No. 2514 is expressed in simple and progressive chemical changes; there are progressive increases of SiO_2, Al_2O_3 and total alkalies, and progressive decrease of MgO, CaO and total FeO, together with MnO. TiO_2 and P_2O_5 show slight increase in No. 2314, but after which they both decrease in No. 2514. The appinite is /

is chemically between the feldspathic hornblendite and the rocks of Ach'uaine type and the adjacent granodiorite.

From the foregoing summary of chemical changes, it is evident that the alteration of the original hornblendic rocks of Durcha type to rocks of Ach'uaine type through the stages of basified hornblendic Moine rocks involved as a whole the increase of

MgO, CaO, (total $FeO + MgO + CaO$), K_2O, H_2O, P_2O_5, TiO_2 and MnO.

This assemblage of introduced materials may be corelatted with the constituents that migrated outwards from the region of migmatisation and granitisation. It seems to be confirmed by Cheng's findings in the Bettyhill migmatite area (1944) where the development of permeation-gneiss from the pelitic rocks involved fixation of incoming Na, Al, and Mg and the driving out of Si, Fe, Ca, K, Ti, P and Mn. Similarly, it is found that the development of fine migmatitic granite from fine semi-pelitic migmatite involved the introduction of at least Na, Al and Ca, and the driving out of Fe, Mg, K and H. These constituents (with the exception of some of the Si), which migrated outwards from the region of migmatisation and granitisation, are precisely those that were introduced in the basified hornblendic Moine rocks and the rocks /

rocks of Ach'uaine type during the stages of basification and desilication.

Comparison may also be made with the chemical relations of biotite-rich schists to the albite-schists of the Dalradian Series in the Caledonian fold region of the South-western Highlands and Antrim (Reynolds, 1942). The albite-schists bear witness to the operation of geochemical migration in the orogenic belt. Reynolds demonstrated that the incoming of Na and Si into the schists, in which albite porphyroblasts appear, has led to the concomitant driving out of Al, Fe, Mg, Ca, K, H and Ti. These constituents must have migrated and become fixed (in part) at some other position beyond the locus of albitisation, there leading, for example, to the development of rocks like the biotite-schist.

Here again, we have the same assemblage of constituents (with the exception of the Al) as that required for the transformation of hornblendic rocks of Durcha Type to basified hornblendic Moine rocks and rocks of Ach'uaine type. The assemblage is that of a typical basic front.

The fixation and culmination of the basic constituents, and their relative proportions within the basic front are, however, differential. The sequence at any time would be a sequence in space, at any point the sequence is a sequence /

sequence in time. Thus, each specific rock type within the basic front now represents a subsidiary maximum concentration of some constituents. The nature of these concentrations can be readily followed by reference to Fig. 10. The relict hornblendic Moine rock No. 3014 represents a Mg culmination; the relict hornblendic Moine rock with pyroxene patches No. 313, represents the culmination of Ca, total Fe + Mg + Ca and P; the diopside-rich mela-syenodiorite No. 1125 represents the culmination of Ti; and the biotite-rich mela-syenodiorite No. 614 represents the culmination of K and H. It is interesting to note that among the minor constituents P usually reaches its culmination first in the initially basified rocks and Ti attains its culmination only subsequently. This fact may have a wider application in regions of basification.

With the advancement of true granitisation these initially basified rocks themselves become granitised and, in accordance with such change, all the cafemic constituents Ti, P and Mn decrease in amount and the Si, Al and alkalies reach culmination in the granodiorite.

Fe, Mg, Ca and Mn displaced from these basic rocks during their granitisation are now represented in the feldspathic hornblendite rims and clots that represent a local basic front developed during the granitisation of the basic rocks.

The /

The chemical relationship between the various members are pictorially expressed in a von Wolff diagram (Fig.11). The von Wolff diagram has the advantage of separating the feldspathic from the ferromagnesian constituents and chemically undersaturated from the chemically oversaturated, thus emphasises the contrast between the rocks of the basification series and the granitisation series.

The initial <u>basification</u> + silication is seen in the sequence (1) Hornblendic Moine rocks No. 1330 ⟶ Relict hornblendic rocks No. 3014 ⟶ Relict hornblendic rocks with pyroxene patches No. 313. This followed by the desilication and feldspathisation stage as shown from (2) Relict hornblendic rock with pyroxene patches No. 313 to the field of rocks of Ach'uaine type (Nos. 1223, 1125 and 614); (3) the further granitisation of the basic rocks is exhibited in the continued gradation from rocks of Ach'uaine type through appinite No. 2314 to granodiorite. The granitisation of the basic rocks give rise to (4) the complementary development of local basic front, as examplified by feldspathic hornblendite No. 1214. The change from rocks of Ach'uaine type to feldspathic hornblendite is essentially one of basification.

2. /

2. Rocks of Ach'uaine and Appinite type in the zone of Moine rocks.

In section III, 2 (d), pp.38-9 of this thesis, it was shown that small basic masses (Nos. 1-7), occurring in the form of sills and dykes in the zone of Moine granulites, have apparently been produced by the transformation of epi-diorite sills and dykes as a result of long-range migration beyond the zone of migmatisation andgranitisation. They represent a peripheral basic front.

This transformation is made clear by comparing the three analyses of epidiorite (Table II) with the three analyses of 'Hybrid rocks of Ach'uaine Type' quoted from Read (1926, p. 163) in Table XII.

TABLE /

TABLE XII

	I	II	III
SiO_2	37.78	53.25	57.28
TiO_2	1.93	1.26	0.85
Al_2O_3	11.83	14.20	15.75
Fe_2O_3	2.46	2.94	2.37
Cr_2O_3	0.19	trace	-
V_2O_3	0.02	nt.fd.	-
FeO	4.34	3.60	2.14
MnO	0.41	0.31	0.20
CaO	15.31	7.44	5.48
MgO	11.22	5.40	3.38
K_2O	4.29	5.00	5.04
Na_2O	0.62	3.20	3.87
H_2O at 105°C	0.15	0.16	0.06
H_2O+ 105°C	1.24	0.88	0.93
P_2O_5	0.53	0.52	0.52
FeS_2	0.10	1.04	nt.fd.
CO_2	7.80	2.01	2.32
	100.22	100.21	100.19

von Wolff Values

I.	Q	=	-23.06
	L	=	46.92
	M	=	76.12
II.	Q	=	- 3.93
	L	=	65.48
	M	=	38.44
III.	Q	=	2.41
	L	=	73.68
	M	=	23.90

Analyst: E.G. Radley

I. Basic Hybrid of Ach'uaine Type, No. 21423, with no more than 10% of feldspar, the chief components being biotite, pyroxene and scarce hornblende, abundant accessory apatite and small amounts of sphene and calcite. The dominant feldspar is a slightly perthitic orthoclase; albite-oligoclase is rare. The analysed rock was collected from 500 yds. west-south-west of Ach'uaine, three miles E.10 S. of Invershin Station, Sutherland.

II. Intermediate Hybrid of Ach'uaine Types, No. 21424, wit about 50% alkali-feldspar, abundant biotite and hornblende, rare calcitised pyroxene and accessory apatite, sphene and calcite. The rock was collected from the summit of Cnoc a Choire Bhuidhe, 1300 yds. west-north-west of Ach'uaine, Sutherla

III. Intermediate Hybrid of Ach'uaine Type, No. 21425, with mineral composition similar to that of II (No. 21424). The rock was collected near the summit of Cnoc a Choire Bhuidhe, 1600 yds. W.15 N. of Ach'uaine, Sutherland.

(All three descriptions from Read, 1926, p. 164)

In order to determine the relation between the analysed 'Hybrid rocks of Ach'uaine Type' of the Ach'uaine area and the rocks found during the course of the present investigation, the writer visited the type localities of the Ach'uaine area in the field and studied the original specimens and slides of the analysed rocks at the headquarters of the Geological Survey in London. He found that all the basic masses, except one at Beinn Dònuill which is situated at the margin of the Migdale granite, are in Moine granulites occurring in the aureole of the Migdale granite. Thus, they are comparable to the small basic masses found in the Moine granulites around Loch Iain Bhuidhe and Meall Clais nan Eath in the Rogart area. The analysed specimens were collected from among the thirty small masses which outcrop in an area of one square mile near Ach'uaine, two and a half miles north-north-east of Bonar Bridge. These masses are slightly granitised and have locally been transformed into agmatites.

Mineralogically, the basic 'Hybrid' I is a biotite-pyroxenite, which is comparable to the basic member of the rocks of Ach'uaine type described in this thesis (p. 76). The intermediate 'Hybrids' II and III, are hornblende- and biotite-rich rocks and both slides contain abundant orthoclase in addition to the plagioclase. Thus according to the present /

present classification they correspond to members of the appinitic group, and represent intermediate stages between the biotite-pyroxenite and the granodiorite.

Comparing the chemical analysis of the basic 'Hybrids' No. I, with those of the epidiorites (Nos. 1, 2 and 3, Table II), it can be seen that the transformation from epidiorites to biotite-pyroxenite involves decrease of SiO_2 Na_2O, Al_2O_3 and total FeO, and complementary increase of MgO, CaO and K_2O, together with TiO_2, MnO and P_2O_5. The change is therefore essentially one of basification.

The granitisation series, as examplified by the continued gradation from biotite-pyroxenite (I) through the appinites (II and III) to granodiorite (No. 2514, Table X), involved as a whole the decrease of MgO, CaO, FeO, together with TiO_2, P_2O_5, and MnO, and the concomitant increase of SiO_2, Al_2O_3 and Na_2O. K_2O has culminated in II and III, but falls again in No. 2514.

The von Wolff diagram, Fig. 12 , shows distinctly the chemical relationship between the various members of Read's 'Hybrid rocks of Ach'uaine Type' and the epidiorites and granodiorites. It is clear from the diagram that the basic 'Hybrid' I represents the basification stage of the transformation of the epidiorites Nos. 1, 2 and 3, while the subsequent /

subsequent granitisation series is exhibited in the continued gradation from biotite-pyroxenite through the appinites II and III, to granodiorite (No. 2514).

The writer has already, in the field description, p.38, advanced the view that the basic masses of Ach'uaine type occurring in the Moine granulites (Nos. 1-7) within the aureole of the xone of migmatites and granodiorite have a similar field occurrence to that of the epidiorite - skarn sills of the Malin Head area of Co. Donegal, recently studied in great detail by Holmes and Reynolds (1947). These authors have traced the transformation of an epidiorite sill through the following stages:

Epidiorite ⟶ Biotite-epidiorite ⟶ Biotite-skarn ⟶ Lepidomelane skarn / Chlorite-skarn

They found that this transformation involved the fixation of MgO, (total FeO + MgO), K_2O, H_2O, P_2O_5 and MnO, with concomitant driving out of Al_2O_3, CaO and Na_2O. They have also shown in addition to the findings of Lapadu-Hargues (1945), that K not only culminates in the granitic rocks but also migrates outwards into the basic front together with other elements of small ionic radii, i.e. Fe and Mg.

Here in the Rogart area, the transformation from epidiorite to biotite-pyroxenite (the most basic member of the 'Rocks /

'Rocks of Ach'uaine Type') requires an assemblage of constituents essentially similar to that required for the formation of skarn-rocks from epidiorites (apart from the differing behaviour of CaO). The migrations involved in both examples, were of the long-range type characteristic of the zone of regional metamorphism surrounding migmatite fields.

The sequence in the development of the rock types in the Rogart migmatite field shows very clearly that the migmatisation and granitisation depend on a complex chain of ionic migrations, with balanced additions and subtractions, so that while some of the rocks undergoing migmatisation and granitisation approach the composition of granite, others receive additions including Fe and Mg, and become more basic. Moreover, this interdependence of process of granitisation and basification seems a general phenomenon in all areas of regional metamorphism. In a geochemical study of rocks of varying regional metamorphic grades, Lapadu-Hargues (1945) found that the distribution of chemical elements can be co-related with the metamorphic grade. Thus Fe'' and Mg are concentrated in the frontal zone of regional metamorphism and decrease through the higher grades. Total alkalies increase progressively from the lower to higher grade rocks; but in the lower grades of metamorphism Na increases relative to K, while /

while in the higher grades (granitisation) both Na and K increase. Ca increases gradually as the metamorphic grade increases, and reaches its maximum in the granites. Lapadu-Hargues finds the order of increasing mobility to be: K, Ca, Na, Mg, Fe; and he correlates this order of the elements with their respective ionic radii. The small ions, such as Fe and Mg, migrated the farthest.

Reference may also be made to a recent study of the chemistry of rocks associated with granite by Reynolds (1946), who has demonstrated that in every example which had received adequate chemical study, the emplacement of granitic bodies has been accompanied by the introduction of cafemic constituents and alkalies (commonly K) into both aureoles and inclusions. Only subsequently have these initially basified rocks been granitised.

From the relevant chemical data it is apparent that a basic front is in fact a zone within which the chemical bases have increased to such extent that the rock has become molecularly desilicated relative to the molecular proportion of the bases present. Reynolds (1946, p. 390) showed that "When the desilication change is wholly or largely one of basification (introduction of Fe, Mg, Ca) it is characterized by increase, commonly attaining geochemical culmination, of one /

one or more of the minor constituents TiO_2, P_2O_5 and MnO; when it is essentially one of feldspathization, however, TiO_2, P_2O_5 and MnO may all decrease". With this conclusion the Rogart evidence is completely in accord.

Finally, it may be noticed that the basic front in the Rogart migmatite area is not really a 'front' of the simple kind that the word originally indicated. The cafemic constituents driven out from the migmatised and granitised region have become fixed most abundantly and conspicuously in separate hornblendic bodies insteadof in an uniform frontal zone. This complication, however, has been made intelligible by Reynolds in her additional explanation of the proper use of the term. She states: "A front occurs whenever there is a diffusion limit marked by a change in the mineral assemblage ...... relics within the granite, the zone margining the main region of granitisation, and the country rocks encasing the granite pods, become subjected to the advance of an Fe-Mg front, and may finally be by-passed by the 'invading' granite, or become more or less granitised. Fe-Mg fronts are particularly strongly developed within the rocks that were initially relatively basic, and, in consequence, these rocks commonly remain as highly basic or ultrabasic relics within granite". (Reynolds, 1947, p. 211).

VII. COMPARISON WITH OTHER AREAS

In the Northern Highlands the rock series most comparable with the Rogart assemblage is that of the Hornblendic Complex of the Bettyhill migmatite area described by Cheng (1942). This complex includes rocks resembling both the Hybrids of Ach'uaine Type of central Sutherland and the Appinitic Suites of the South-western Highlands. The petrological members are pyroxenite, hornblendite, hornblend-pyroxene-biotite-schist and coarse appinites together with their migmatitic derivatives such as appinites, pseudo-dioritic gneisses, hornblendic augen-gneisses and streaky granite-gneisses. The parent rocks were shown by Cheng to be older than the period of general migmatisation and were believed by him to have resulted from a process of hybridisation that was completed before the general migmatisation. This had the effect of rendering these rocks more easily affected by the later migmatisation than were the associated sedimentary Moine rocks.

The writer has already in a previous communication (Ma, 1948) and p. 161 of this thesis, pointed out that it was unnecessary to introduce a hybridisation stage. Moreover, Cheng, like many other geologists who have worked in migmatite /

migmatite areas, failed to recognise the evolutionaly sequence of the basic rocks. Nevertheless, in his field observations he drew attention to the gradations between the various petrological members; for instance (Cheng, 1942): "Hornblende-pyroxene-schists are seen to pass into hornblendite, ... On the strike of the last bands are found coarse appinitic types which pass into streaky and patchy hornblende-feldspar-rocks" (pp. 69-70), and "..... hornblende-pyroxene-biotite-schist invaded by numerous granitic sheets ...... with development of large hornblende prisms in a coarse appinitic rock at the immediate contact" (p. 70). The writer has examined the area described by Cheng and from the observed field relations, he finds that the evolutionary rock sequence in the Bettyhill area corresponds exactly to that of the Rogart area. He has therefore no hesitation in suggesting that the Bettyhill rocks have been formed by the operation of the same processes. The complete sequence of changes through which the basic rocks of Bettyhill area have passed is probably as indicated schematically below:

← Basification Series —

Amphibolite → { Pyroxenite / Hornblende-pyroxene schists / Hornblende-pyroxene-biotite schists } → Hornblendite

← Granitisation Series —

(Hornblendite) → Appinitic rocks → Hornblendic migmatites → Augen-gneiss / Hornblendi[c]

Another /

Another related example is provided by the rocks of the appinite suite associated with the Movern-Strontian 'granite' in the South-western Highlands (MacGregor and Kennedy 1932). In the petrology section of this thesis, pp. 92-93 evidence has already been presented that the appinite suite of Morven and Strontian area includes not only appinite (as originally defined by Bailey) but also rocks of Ach'uaine type. This is evident as we can see from the following statement: "In connection with the associated basic hornblendic rocks it may be stated that there are few, if any, of the Survey hand-specimens of the 'Ach'uaine Hybrids' of Sutherland, that cannot be exactly matched by specimens of the Appinite-Lamprophyre Suite from Morven, Sunart and Moidart", (MacGregor and Kennedy, 1932, p. 119). More petrological detail, of course, is desirable before any close comparison of the different stages of transformation can be made, but judging from the similarity of the geological settings and the rock assemblages of both regions, it seems likely that these appinitic rocks owe their origin to processes akin to those responsible for the formation of the rocks of Ach'uaine and Appinite types in the Rogart area.

It may be pointed out in passing, as being possibly related to the subject matter of the present study, that in many /

many plutonic complexes the main 'granite' is characterised by a marginal phase of shonkinitic rocks. Examples are (a) the well known plutonic mass described by Pirsson (1900) at Yogo Peak, Montana, where shonkinite forms the actual border of the mass at both ends and passes gradually into the middle portion of porphyritic granite through monzonite and banatite (syenite); and (b) the shonkinite of Basswood type near the border of four distinct (so-called) Algoman granite masses in Minnesota (Grout, 1925). In concluding the description of this peculiar shonkinite, Grout stated: "It is expected that shonkinites (Basswood type) may be found in many places related to granite; and they grade on one side into syenite, and on the other into hornblendite. No doubt there may be also gradations to dioritic rocks", (1925, p. 479). Attention has already called to the similarity of the appinite of Rogart area with the hornblendic variety of the shonkinite of Basswood type, and from the above statement the similarity of the rock sequences in both areas is also apparent.

These examples have been commonly regarded as normal products of magmatic differentiation, but in the light of the observations made during the present investigation, such shonkinitic marginal phases are likely to represent zones of cafemic /

cafemic enrichment complementary to the development of 'granite' bodies. They may have originated from pre-existing basic rocks (either sedimentary or igneous origin) by desilication dependent on feldspathisation and/or basification. The characteristic sequence is probably:

country rock (sedimentary or igneous, basic in composition) ⟶ basic 'igneous-looking' rocks (shonkinite or other types) ⟶ granite.

Another series of rocks with a general resemblance to the rocks if Ach'uaine and Appinite types of the Rogart area is that of the basic roof rocks of the eastern end of the Newry Complex, comprising the following gradational series:

sediment ⟶ mobilised sediment ⟶ syenite ⟶ monzonite ⟶ shonkinitic monzonite ⟶ biotite-pyroxenite

These have been described by Reynolds (1934, 1936, 1944) as representing an Fe-Mg-Ca front proceeding in advance of the granitisation process which give rise to the Newry granodiorite. The desilication change from sediment to syenite is essentially one of enrichment of alkalies, whilst the further change from syenite through monzonitic types to biotite-pyroxenite is predominantly one of basification, with enrichment in Fe, Mg and Ca. Thus, in the Newry area, as a post-tectonic granite body was emplaced, it was preceded by /

by a zone of molecular desilication of the country rock sediments (the basic front) composed of an outer aureole of enrichment in alkalies, and an inner one of enrichment in Fe, Mg and Ca.

VIII. ACKNOWLEDGMENTS

The writer came to Scotland to investigate problems of granitisation and associated petrogenetic phenomena in the year 1946, and the investigation of part of the Rogart area was suggested to him by Professor Arthur Holmes, because of the wealth of interest so well exposed in the rocks there. In concluding this thesis the writer wishes to express his indebtedness to Professor Arthur Holmes for advice, encouragement and constructive criticism given to him during the whole period of research.

Thanks are also due to Dr. Robert Campbell for encouragement and instructive discussion. He also greatly helped by placing apparatus for microscopic studies at the writer's disposal.

The writer is most grateful to Dr. Doris L. Reynolds for her inspiring suggestions, constant help during the course of the work, and allowing him to read and refer to her unpublished type-scripts. Indeed, without her help this thesis might never have taken its present form.

The writer was enabled to come to Britain and undertake this work by the generosity of the British Council; for this, as well as for the financial aid to meet the expenses of chemical analyses, he desires to thank the British Council.

IX. LIST OF WORKS TO WHICH REFERENCE IS MADE.

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APPENDIX

On the Occurrence of Agmatite in the Rogart Migmatite Area, Sutherland
A Study in Granitization

BY

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Reprinted from the Geological Magazine, Vol. LXXXV, No. 1,
January–February, 1948, pp. 1–18.

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On the Occurrence of Agmatite in the Rogart Migmatite Area, Sutherland : A Study in Granitization

By HSING-YUAN MA

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(PLATE I)

I. INTRODUCTION

AGMATITE was one of the new descriptive terms introduced by the late Professor J. J. Sederholm in connection with his life-long study of the Finnish migmatites. He applied this name to a group of migmatites which present an appearance that has suggested the terms " eruptive breccia " and " intrusion breccia ", but agmatite has a very different genesis from that connoted by these terms. Of agmatites

Sederholm (1923, p. 117) wrote : " As these migmatites consisting of fragments of older rocks cemented by granite are genetically and petrologically very different from many of the rocks that have been called eruptive breccias many of which are volcanic rocks, the author proposes to designate this group of migmatites as *agmatites* (from ἄγμα, fragment)." The elaborate drawings and illustrations to be found in Sederholm's Memoirs (1923, 1926), however, give a much clearer idea of the appearance presented by these rocks than any written description.

In 1938, C. E. Wegmann (pp. 40–41) further emphasized the desirability of retaining agmatite as a purely descriptive term, writing : " It would be convenient, therefore, to give the term agmatite a merely descriptive meaning, that is to say, to let it denote merely a fragmental rock with a more or less granitic cement, saying nothing about its genesis. In so doing, we may reserve the genetically influenced conception 'intrusive breccia' for such cases in which the intrusion mechanics can be ascertained."

As long ago as 1925 Read (p. 33) pointed out the similarities between the migmatites and associated rocks of Rogart and those of Fennoskandia, which had already been made famous by the classical studies of Sederholm. In the former area a central granodiorite body is followed outward by a zone of migmatites which show, along the strike, every stage of transition to the various normal lithological types of the Moine country rocks. In the migmatite zone as a whole the main types of Moine rocks that formed the framework from which the migmatites were developed are siliceous granulites and semipelitic rocks ; in addition there are subordinate pelitic schists, hornblendic rocks, and biotite-hornblende-schists, and smaller occurrences of more basic schists, e.g. hornblende-biotite-pyroxene-schists, that originated as dykes. Referring to the appearance of the fine grained biotite- and biotite-hornblende-schists in the migmatites, Read (1925, p. 27) stated : " these are intricately veined with thin strings of granitic material rather than soaked or lit-par-lit injected." In other words, they assume the form of agmatites. The writer has repeatedly noted this same phenomenon in the field and has found that it is characteristic both of the fine grained biotite-hornblende-schist and of the more basic schist of hornblende-biotite-pyroxene composition. Whereas the granulitic and semipelitic rocks commonly give rise to striped migmatites, the more compact basic varieties now appear as agmatites. This paper gives a brief account of the mode of occurrence of two types of agmatites and of the mineralogical and petrological changes that have taken place during their formation. The migmatization of the main Moine types and the origin of the granodiorite are to be described in another communication.

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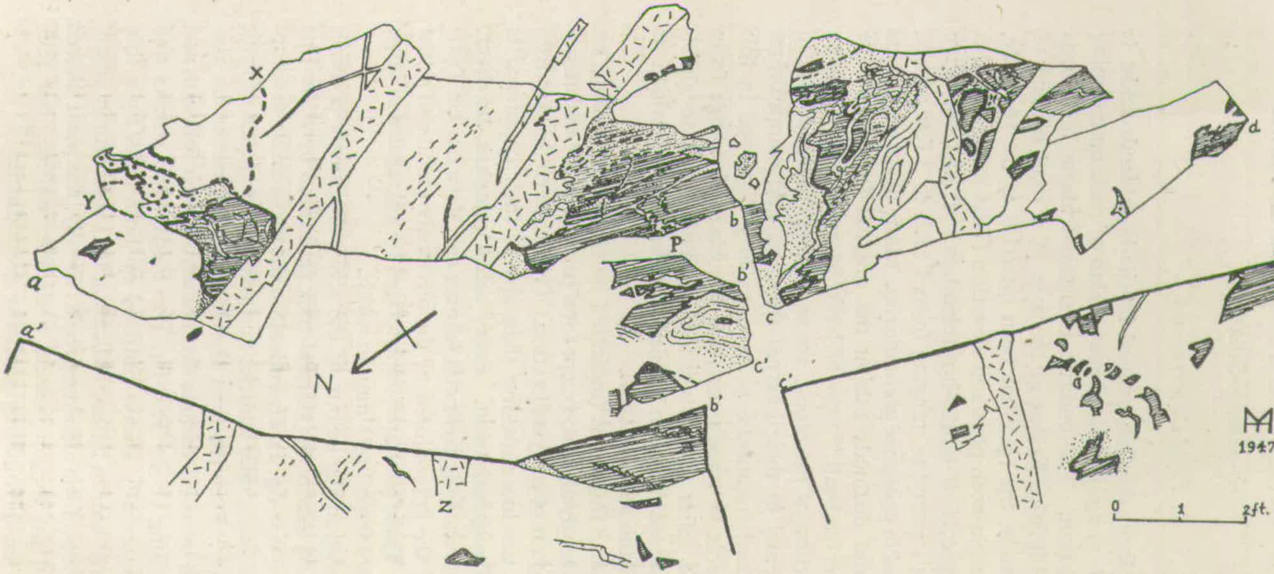
II. Agmatite Developed from a Fine Grained Biotite-Hornblende-Schist

1. *Field Observations*

Agmatite formed from the fine grained biotite-hornblende-schist is to be seen at its best on a polished, glaciated slab of rock outcropping south of Rogart Station. The outcrop is situated about 225 yards north-east of the Millnafua Bridge at the side of a road leading to Splockhill. Fortunately, the rock has been quarried at the roadside, and so can be studied in both plan and elevation (Text-fig. 1) and Figs 94-6. In this slab dozens of fragments of biotite-hornblende-schist, and very rare fragments of siliceous granulite, ranging from 1 inch to 3 feet across, can be seen embedded in gneissose granodiorite. Many of the fragments are quite angular and distinctly exhibit the original features of the fine grained " pepper-and-salt " type of basic Moine schist. Others, as in the middle portion of the block, are very much changed both in their external form and in their internal structure and composition. By studying individual fragments, so spectacularly displayed in this exposure, it is possible to trace a complete sequence of change from practically unaltered relics of the biotite-hornblende-schist to ghost-like remnants dispersed through gneissose granodiorite which is itself a migmatite of the nebulite type.

Many of the angular fragments (indicated by close line shading on Text-fig. 1) are but slightly altered, except for a partial loss of schistosity due to a certain amount of recrystallization. This leads to the development of rocks that are more massive than any of their counterparts outside the area of migmatization. Every schist remnant, however, invariably exhibits a relatively basic rim (shown as a dark line on Text-fig. 1) against either the granodiorite or the obviously granitized schist as the case may be. These rims are characterized by aggregates of large biotite flakes and vary from 1 to 3 mm. in width.

With further alteration the colour of the schist fragments becomes gradually lighter than that of the normal rock (indicated by wider line shading and dots on Text-fig. 1), dependent on the progressive development within them of leucocratic lenticles and veinlets composed of sodic oligoclase and quartz. Even the least altered schist fragments are also sometimes traversed by small veinlets that cut across their foliation and show ptygmatic folding (P on Text-fig. 1). Feldspathic streaks and veinlets alike are practically always outlined on both sides by a thin film of relatively large biotite flakes, indicating that their emplacement involved a basification of the adjoining rock. Finally, the most altered fragments of schist no longer possess a definite outline, but fade imperceptibly into the surrounding gneissose granodiorite.



TEXT-FIG. 1

TEXT-FIG. 1.—A petrological sketch of a rock slab at the road-side, 225 yards N.N.E. of Millnafua Bridge, Rogart. The sketch shows an agmatite developed from a biotite-hornblende-schist. The upper portion is a map of the horizontal surface. The lower portions, *a'b'*, *b'c'*, *c'd'*, are the exposed elevations corresponding to the edges *ab*, *bc*, *cd* of the map. Line shading = biotite-hornblende-schist fragments bounded by biotite-rich rims, shown by heavy black lines, the thickness of which is slightly exaggerated for clarity of reproduction ; combined lines and dots = slightly granitized schist, with heavy dashed lines representing lines of biotite ; dots = dioritic migmatite ; white = granodiorite, with relict biotite and hornblende selvedges shown as heavy dashed and curved lines ; criss-cross lines = white granite. For a detailed description see pp. 3–5.

The granodiorite within which the schist fragments are embedded is characterized by strings of biotite (heavy dashed and curved lines on Text-fig. 1) with which hornblende is sometimes associated. Such basic streaks not only have every appearance of being relics of basic selvedges that originally outlined schist fragments, but they can sometimes be traced in continuity with such basic margins of schist. Such a continuity is seen at the western end of the exposure, and is indicated at X–Y in Text-fig. 1.

Whereas the fragments of biotite-hornblende-schist can be seen in every stage of conversion to gneissose granodiorite, conversely, the granodiorite, in its foliation and basic selvedge residuals, exhibits evidence of having developed by replacement of biotite-hornblende-schist. The agmatite as a whole has therefore been developed *in situ* as a result of the granitization of biotite-hornblende-schist. From the field evidence it is clear that step by step as biotite-hornblende-schist was granitized, the surplus basic materials were driven from the loci of granitization and fixed within the biotite-hornblende-schist. In the development of the initial arteries of granodiorite the surplus basic materials were driven into the residuals of schist, along the margins of which they developed basic rims. With the further advance of granitization, streaks and veinlets of granodiorite developed within the schist fragments, and in their turn became margined by basic selvedges. Finally, granodiorite characterized by biotite lenticles and streaks, residuals of basic margins, resulted.

Veins of biotite-poor granite cut through the agmatite. Since they generally cut across the greyish gneissose granodiorite with straight junctions it is clear that in this particular place their development post-dated the processes of migmatization. In some parts of the veins, however, the contact is not sharp, but shows gradation to the migmatite and granodiorite. An example of such a gradation was found at Z in Text-fig. 1. Moreover, where the margins of the veins are irregular the irregularities link up with the feldspathic streaks in the schist. Further, the margins of the veins are, in nearly all cases, bordered with a thin film of biotite. These features suggest that the veins may have been formed as a result of the continuation of the same processes that gave rise to the development of the feldspathic streaks and veinlets within the biotite-hornblende-schist.

2. *Petrology*

(*a*) *The biotite-hornblende-schist.*

The fine-grained biotite-hornblende-schist is a dark greyish black schistose rock consisting essentially of granoblastic plagioclase and quartz with small hornblende prisms and biotite flakes in subparallel arrangement. The plagioclase is a basic oligoclase An_{27}; it forms xenoblastic crystals, often slightly sericitized in the central portion. It is the most abundant constituent, and is followed in order of decreasing abundance by hornblende, biotite, and quartz. The biotite shows a pleochroic scheme of X = straw yellow < Y = Z = dark brown to black. The hornblende has 2V = ca 90°, $Z \wedge C = 23°$ and X = yellowish green < Y = green < Z = green with a bluish tinge. Quartz occurs as rare irregular grains. Accessories are sphene, apatite, zircon, chlorite, and ores, and the abundance of sphene is very noteworthy.

(*b*) *Biotite enrichment of the biotite-hornblende-schist.*

Where in juxtaposition with granitic material the schist exhibits a gradual loss of schistosity, becoming more lustrous and darker in colour. In thin section (1817) it is seen that the biotite has increased both in size and in quantity, whereas the hornblende has considerably decreased in amount. The abundance of large crystals of sphene and needles of apatite is also very noteworthy.

(*c*) *Migmatitic rocks derived from the biotite-hornblende-schist.*

With further changes the resulting rock shows abundant granitic areas along the " s " planes. The granitic lenses and strings are always rimmed with biotite flakes which serve to mark out the original structure. The most noteworthy feature, found in thin section (717*a*), is the increase in grain size and amount of the plagioclase and quartz. Quartz forms large irregular individuals, sometimes as much as 1·5 mm. across, which show slightly sutured contacts against the neighbouring plagioclase. The latter mineral, a basic oligoclase, occurs as subhedral crystals which are occasionally blebbed with rounded quartz. Biotite flakes and some relict hornblende have a subparallel arrangement as in the initial schist. The accessories, sphene and apatite, etc., have decreased in amount in comparison with the rocks described under (*a*) and (*b*).

(*d*) *The Gneissose Granodiorite.*

This rock, which represents the last stage of alteration of the schist, has a slightly foliated appearance marked by streaks of biotite and hornblende. In thin section (317) the granodiorite is found to be characterized by large porphyroblasts of orthoclase which developed chiefly at the expense of the plagioclase. The replacement resulted in a highly irregular sutured and saw-like junction between the two minerals, and some relict patches of sericitized oligoclase remain enclosed within the replacing orthoclase, still in optical continuity with the unreplaced portion outside. Clear rims of more acid oligoclase or even albite are found at the contact between the sericitized oligoclase and the replacing orthoclase. The former mineral sometimes shows a marginal development of cauliflower-shaped myrmekite, the lobes of which project towards the orthoclase. Quartz shows sutured contacts against the oligoclase and occasionally includes this mineral. Biotite is sometimes chloritized. Other accessories are sphene, apatite, green biotite, zircon, orthite, chlorite, and ores.

(*e*) *Geochemistry of the Transformations.*

In order to determine more exactly the mineralogical and chemical changes that took place during the migmatization of the biotite-hornblende-schist, micrometric measurements of the specimens described above were made and are recorded in Table I.

TABLE I.—MODES OF THE BIOTITE-HORNBLENDE-SCHIST AND ITS MIGMATITIC DERIVATIVES (VOLUME PERCENTAGES).

	A	B	C	D
Quartz	4·14	6·59	23·28	22·26
Plagioclase . . .	38·87	33·92	59·70	43·26
Orthoclase	—	—	·50	14·86
Myrmekite . . .	—	—	—	3·63
Biotite	20·74	38·23	13·01	13·59
Hornblende . . .	30·25	13·63	1·88	1·44
Sphene	5·48	5·42	·49	—
Apatite, chlorite, ore, etc. .	·53	2·18	·99	1·01
	100·01	99·97	99·85	100·05

A. Biotite-hornblende-schist, No. 1717.
B. Biotite-enriched biotite-hornblende-schist, No. 1817.
C. Migmatite of dioritic composition, average of Nos. 717 *a* and *b*.
D. Granodiorite, average of Nos. 317 and 1117.

The most noticeable mineralogical change from A to B is biotite enrichment ; such a change implies an increase in the K_2O and in the total of iron oxides and MgO. It also implies a decrease of CaO.

In the initial stage of migmatization illustrated by the passage from B to C there is an increase in the amount of plagioclase and quartz, and a concomitant decline in the amount of hornblende and biotite. At this stage of migmatization the chemical changes must have involved at least an increase of SiO_2 and Na_2O, with a concomitant decrease in at least K_2O, FeO, MgO, TiO_2, and P_2O_5.

The material lost in the initial stage of migmatization would adequately account for the development of the biotite-rich rims along the margins of the newly-developed leucocratic lenses and veinlets. It is also clear that the introduction of similar materials into the initial biotite-hornblende-schist would account for the biotitization that gave rise to the basic rims around schist fragments. Granitization and biotitization thus appear as complementary processes ; as one portion of the biotite-hornblende-schist was granitized, K_2O and total

FeO + MgO decreased and the adjacent part of the schist became enriched in these materials.

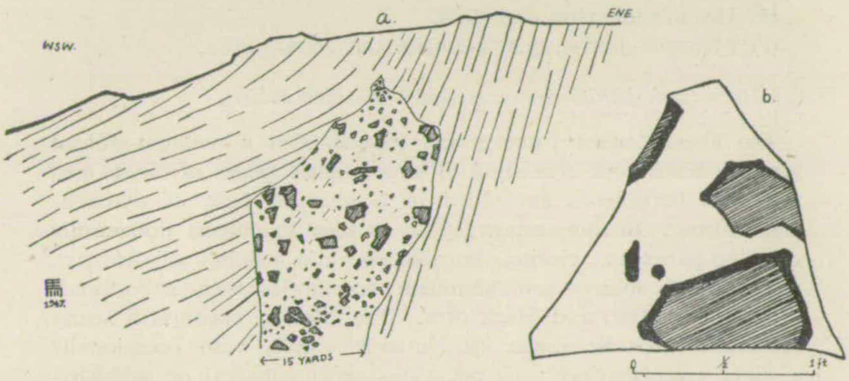
In the final change from C to D the fact that oligoclase was replaced by orthoclase, whilst the percentage of biotite remained essentially unaltered, implies that there was an influx of K and a loss of Na. Here again a complementary relationship is apparent, for the formation of the granodiorite involved the liberation of Na necessary for the development of more dioritic rock like that of the preceding stage of change. It should perhaps be emphasized by way of explanation that the complementary changes that are here described as a sequence in time, must, as granitization progressed, have also proceeded as a progressive sequence in space, so that materials liberated at one locus would become available at another.

III. Agmatite Developed from a Basic Schist of Igneous Origin

1. *Field Observations*

Another group of agmatites is found in basic schist bodies that represent a series of older basic igneous dykes. These were intruded prior to the period of Moine metamorphism during which they, together with the country rocks, were rendered schistose. The basic schist bodies are all more or less elongated in shape, and none of them attain great size. They usually truncate the bedding of the Moine rocks, thus indicating that they were of intrusive emplacement. During the first stage of migmatization, these bodies are commonly intricately veined with thin strings of granitic material that is more resistant than the schist and stands out after weathering as small ridges, thus giving the rock a honeycombed appearance. The further stage of migmatization is characterized by the widening of the granitic portions and the dissection of the schist into isolated angular fragments.

The example of agmatite here presented (Text-fig. 2*a* and Pl. I, fig. 2) is taken from the largest of these bodies, which is situated on the eastern side of Creag a' Bhata at the small rock cliff above the hill-path from Pittentrail to Little Rogart. The body is roughly lenticular in plan, the widest part measuring about 20 yards and the length about 50 yards. It has a vertical dip crossing the bedding of the Moine granulites. Granulites and dyke alike have been granitized. The granitization follows the bedding in the granulites giving rise to striped migmatites. Within the framework (Text-fig. 2*a*) of the original dyke-shaped schist body, however, the rock has been divided into numerous fragments separated by granodiorite, and is thus now a typical agmatite. The preservation of the original solid framework, with retention of the dyke-shaped form of the schist-body, and lack of disturbance of the bedding of the granulites makes it obvious that the granodiorite was not emplaced as magma. If such had been the case room for its emplacement could only have been provided by either (1) expansion, or (2) downward stoping. It is clear, however, that neither of these mechanisms has been operative, for the original solid framework of the dyke and enclosing granulites is neither distorted nor disturbed, as would be the case if expansion had taken



TEXT-FIG. 2.—(a) A sloping section showing the shape of a basic schist body now represented by agmatite, and its relation to the surrounding migmatized granulites. The fragments inside the body are represented to some extent schematically. Creag a' Bhata, North of Pittentrail, Rogart.

(*b*) A larger scale drawing of part of the rock surface of the agmatite showing basic schist fragments (line shading) with basic rims (solid black), and also residual basic clots in the diorite–granodiorite (white).

place ; and the rocks cannot have sunk for the pre-migmatization geology is still preserved.

Within the agmatite the schist fragments have been altered both chemically and mineralogically, with the production of a great variety of mixed rocks, and although in many of these the characters of the original schist have been in large measure obliterated, we nevertheless commonly find the schistosity preserved, although with progressive alteration it becomes less and less conspicuous. Nearly all the fragments were basified during the first stage of migmatization, as a result of which they now contain pyroxene, biotite, and hornblende. Moreover, every schist fragment is bounded by a basic rim, usually composed of hornblende. Outside the basic rim there is a gradual passage from pyroxene-diorite through quartz-diorite to granodiorite. Within the granodiorite every transition can be found from schist fragments with basic rims to clots, composed mainly of hornblende, which represent the completely basified relics of residual schist.

2. *Petrology*

The petrography of the various rocks composing the agmatite is here presented in the order of the field sequence, passing outwards from the centre of a schist fragment (see Text-fig. 2*b*), under the following headings :—

(*a*) Hornblende-biotite-pyroxene-schist (basified schist).
(*b*) Hornblendic rims and clots.
(*c*) Pyroxene-diorite, quartz-diorite and granodiorite.

(*a*) *Hornblende-biotite-pyroxene-schist (basified schist).*

The altered schist forming the fragments is a medium-grained greenish black rock consisting of large aligned plates of biotite and prisms of hornblende embedded in a greenish base of pyroxene and feldspar. In thin section (10) it is seen to consist dominantly of clino-pyroxene, biotite, hornblende, and patches of feldspar. Apatite and sphene are abundant accessories with subordinate orthite, tremolite, and black ores. The clino-pyroxene is a nearly colourless diopsidic augite ($Z \wedge c = 39°– 40°$), with occasionally a slight greenish tinge ; it occurs as short euhedral or subhedral prisms and is often included in the large crystals of hornblende and biotite. Hornblende with X = light green to colourless < Y = green with a yellowish tinge < Z = green, forms prisms or large patchy crystals up to 5 mm. in length, which are often sieved with feldspar, abundant rounded grains of pyroxene and flecks of biotite. Biotite is pleochroic from pale yellow to brown, and appears both as large plates and as small irregular replacements within the pyroxene. Oligoclase, to some extent sericitized, is the dominant feldspar, but orthoclase is also present in subordinate amount, as large crystals which enclose the other components. Large brownish subhedral crystals of slightly pleochroic sphene, and large stout prisms of apatite up to 2 mm. in length are very abundant ; the apatite usually contains dusty inclusions.

(*b*) *Hornblendic Rims and Clots.*

The narrow rims bounding the schist fragments range from a few mm. up to about half an inch or more in width, and the basic clots in the granodiorite, relics of schist that has been completely basified, may reach a size of 2 or 3 inches across. The latter are irregular in shape. Both rims and clots are built chiefly of large hornblende prisms, 2 by 3 mm. in size, interrupted by sporadic patches of pinkish feldspar. In thin section (44 and 49, see Text-fig. 3) they are found to consist dominantly of large prisms of hornblende with interstitial areas of plagioclase. The accessories, apatite and sphene, are noteworthy both

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for their relatively large size and for their abundance ; they may form as much as 10 per cent of the rock. Other accessories are biotite, pyroxene, and ores. The hornblende has X = pale green < Y = green with a yellowish tinge < Z = green, and is usually characterized by an abundance of inclusions of greenish yellow biotite flecks, pyroxene grains, and small apatite rods. The plagioclase is a sodic oligoclase and is sometimes partly replaced by orthoclase around its margins. The hornblendite of the basic rims and the associated types to which it grades resemble the appinite suite.

TEXT-FIG. 3.—Drawing of part of a thin section to illustrate a narrow basic front of hornblendite forming a rim between granodiorite on the right and hornblende-biotite-pyroxene-schist on the left. Creag a' Bhata. Slice No. 44. A = apatite ; B = biotite ; F = feldspar ; H = hornblende ; P = pyroxene ; Q = quartz ; S = sphene ; solid black = iron oxide ; E = empty holes in the slice. For petrographic details see pp. 10 and 11.

(c) *Pyroxene-diorite, quartz-diorite, and granodiorite.*

The rock outside the hornblendite rims of the schist fragments is very patchy, and includes a series of rock types leading up to granodiorite. The rock immediately outside the rim is a greenish grey, medium-grained, pyroxene-rich rock containing black prisms of hornblende. It is seen in thin section (9) to be a pyroxene-diorite containing stout prisms of pale greenish diopsidic augite with a rough alignment ; their gradual change over to hornblende is in many places well displayed. Large crystals of hornblende, often twinned, are present and measure up to 5 mm. across. They have X = yellowish green < Y = green < Z = green with a bluish tinge. Small rounded inclusions of pyroxene, olive-brown biotite, and apatite occur within the hornblende. Oligoclase, An_{27}, forms irregular crystals ; it is usually sericitized and marginally replaced by orthoclase. Quartz also forms irregular individuals. Apatite and sphene are still comparatively abundant, and it is noteworthy that some of the apatite prisms contain inclusions of pyroxene. Other accessories are green biotite, rutile, and opaque ores.

Further away from the margins of the schist fragments the rock becomes more and more granitic looking, and occasionally contains light greenish pyroxene-rich patches that represent relict ghosts of the basified schist. In thin section (8) a fair amount of clino-pyroxene (5·9 per cent in this particular slice) can still be seen in the rock, but most of it shows various stages of transformation to hornblende. Biotite occurs only as small inclusions within the hornblende. The amount of quartz has increased considerably in comparison with the rocks previously described, and orthoclase is present in small amount.

The final stage of granitization is represented by a more homogeneous granitic-looking rock with hornblende as the only mafic mineral. In thin section, however, it is found to vary from quartz-diorite to granodiorite in composition. The quartz-diorite (7) is composed almost entirely of large individuals of plagioclase and quartz. The former, oligoclase An_{26}, occurs as subhedral crystals which commonly show a combination of fine albite and carlsbad twinning. The quartz exhibits sutured margins towards the plagioclase. In the granodiorite (44*a* and *b*) orthoclase is a conspicuous constituent, forming a quarter of the total feldspar. It has clearly formed by replacement of the oligoclase, of which it often contains optically continuous relics. Moreover, orthoclase can commonly be seen to enclose isolated, though optically continuous, portions of an adjoining crystal of oligoclase. Myrmekite is widespread as cauliflower-shaped protuberances from the plagioclase where it adjoins orthoclase. The oligoclase has a clear margin of more sodic composition where it adjoins the replacing orthoclase. Quartz is very irregular in shape and exhibits sutured margins, typical of replacement, where it adjoins the feldspars. The accessories in both the diorite and the granodiorite are sphene, apatite, biotite, green biotite, and black ores.

(*d*) *Geochemistry of the transformations.*

The results of the micrometric analyses of the various rocks composing the agmatite are set out in Table II. The development of the hornblendic rim F from the basic schist E is one of basification. This is indicated not only by an increase in the sum of the mafic minerals together with a slight increase in the amounts of apatite and sphene, but also by the complementary decrease in the amounts of oligoclase and orthoclase. Chemically the change implies an increase in one or more of the cafemic constituents, and in TiO_2 and P_2O_5, whilst the marked decrease in biotite and orthoclase from E to F indicates a complementary decrease in K_2O. These changes are even more strongly marked in the basic clot, G, that represents a more advanced stage of both basification and desilication of the hornblende-biotite-pyroxene-schist. From a comparative study of a large number of chemical analyses of rocks representing the basic fronts of granitization, D. L. Reynolds (1946) has shown that such basic fronts are particularly characterized by an increase in one or more of the minor constituents TiO_2, P_2O_5, and MnO. By comparing the modes of E, F, and G in Table II, it can be seen that TiO_2 and P_2O_5 have been concentrated differentially within the basic front itself; P_2O_5 first reached its culmination in the basic rims, and TiO_2 subsequently attained its culmination in the basic clots.

TABLE II.—MODES OF THE VARIOUS ROCKS COMPOSING THE AGMATITE DEVELOPED FROM A SCHISTOSE BASIC DYKE (VOLUME PERCENTAGES).

	E	F	G	H	I	J
Quartz	—	·76	—	6·31	34·37	32·07
Oligoclase	9·92	6·59	3·28	40·87	49·83	42·80
Orthoclase	3·18	2·02	1·49	1·87	1·02	14·66
Myrmekite	—	—	—	—	·68	·87
Hornblende	17·16	79·17	85·33	10·81	12·77	8·77
Biotite	25·85	2·62	6·39	—	·32	—
Clinopyroxene	36·82	1·88	1·13	36·25	—	—
Sphene	·57	·71	1·07	·81	·56	·68
Apatite	4·58	4·74	·63	3·04	—	·13
Chlorite, ores, etc.	1·86	1·47	·67	·02	·43	·01
	99·94	99·96	99·99	99·98	99·98	99·99

E. Hornblende-biotite-pyroxene-schist (basified schist), No. 10.
F. Hornblendite rim, No. 44, from the margin of a schist fragment.
G. Basic clot, No. 49, in the granodiorite.
H. Pyroxene-diorite, No. 9, immediately outside a basic rim.
I. Quartz-diorite, No. 7.
J. Granodiorite, average of Nos. 44 *a* and *b*.

The migmatization of the basified schist is seen in the series pyroxene-diorite (H) → quartz-diorite (I) → granodiorite (J). Throughout this rock series the change is essentially one of feldspathization. In the initial stages of migmatization, as exemplified by H and I, oligoclase and quartz show marked increase in amount, the total cafemic minerals decrease, biotite practically disappearing, and pyroxene is gradually replaced by hornblende. As judged from the mineralogy, the chemical changes must have involved the introduction of Na and Si, and the driving out of K, Fe, Mg, and the minor constituents Ti and P.

With the development of granodiorite, representing the final stage of migmatization, orthoclase increased in amount, and there is a complementary decrease in oligoclase together with a further decrease in the cafemic minerals, now represented solely by hornblende, and in apatite and sphene. This stage of granitization involved at least the introduction and fixation of K, which may in part be accounted for by the K liberated in the formation of the basic fronts.

The materials displaced from the basic schist during the migmatization included at least Fe, Mg, Ti, and P, a large part, perhaps all, of which are now represented in the hornblendite clots and rims that represent the basic fronts of the migmatization.

IV. Discussion and Conclusions

From the preceding field and petrological observations it is evident that the two varieties of agmatites described from the Rogart area were formed *in situ* from solid rock as a result of recrystallization dependent on introduction, diffusion, fixation, and expulsion of migrating chemical elements, probably in an ionic state. The agmatites cannot have arisen as a result of intrusion or eruption for such processes would inevitably have caused disruption and displacement of the solid framework of the pre-existing rocks.

The critical field evidences are :—

(*a*) The fragments of the agmatites still retain their original orientation in the unobliterated framework.

(*b*) Considerations arising out of the space problem. If the granitic-looking rocks had resulted from the intrusion of magma there would have been either an increase in volume or a corresponding removal of the country rocks. It is clear in the field that neither phenomenon has taken place.

(*c*) The fragmentary inclusions of the agmatites constitute an evolutionary sequence from indisputable original types, through basified rocks to more or less granitic-looking migmatite with ghost-like relics and basic clots.

The critical mineralogical and textural evidences are :—

(*a*) The replacement habit of many minerals, as exemplified by the relation of potash feldspar to plagioclase and biotite, and of hornblende to clino-pyroxene.

(*b*) The sutured outlines of quartz where it adjoins plagioclase.

(*c*) The development of myrmekite.

(*d*) The poikiloblastic or skeletal character of some of the minerals, e.g. biotite and hornblende.

The fact that the agmatites in the Rogart migmatite area are developed either from the fine-grained biotite-hornblende-schists, or from hornblende-biotite-pyroxene-schists of igneous origin is probably to be related to the more compact nature of these rock types as compared with the main Moine rocks. In consequence the transformation, instead of following well-spaced " s " planes, as in the other members of the Moines, takes place along more irregular routes.

The sequence in the development of the rock types in the evolution of the agmatite is completely in accord with the important conclusions drawn by D. L. Reynolds (1946, p. 390) in her recent study of the chemistry of rocks associated with granite, namely : " just as skarn develops in limestones at granite contacts as a result of the introduction and fixation of iron, magnesium, alkalis, etc., so the initial change in rocks of all types includes enrichment in mafic constituents and alkalis. Only subsequently are the rocks granitized in the strict sense of the term." Moreover the products of the initial desilication change " may attain the composition of syenite or of basic or ultrabasic igneous rocks ", and " when the desilication change is wholly or largely one of basification (introduction of Fe, Mg, Ca) it is characterized by increase, commonly attaining geochemical culmination, of one or more of the minor constituents TiO_2, P_2O_5, and MnO ".

In the first example of agmatite here described the migmatite evolved through quartz-diorite to granodiorite, and in the second example through pyroxene-diorite and quartz-diorite to granodiorite. In both cases the sequence of evolution was thus from more sodic to more potassic varieties. A similar association and sequence in the development of sodic and potassic rocks was found by Y. C. Cheng (1942) in the migmatites of North Sutherland, and by D. L. Reynolds (1943) in the granitized rocks of Goraghwood quarry, Northern Ireland.

The development of the migmatitic, i.e. the granitic portions of the agmatites, was accompanied by the introduction of cafemic constituents and alkalies into the residual schist fragments with the consequent development of basic rims, selvedges, and clots. In the first example such rims and selvedges are characterized by richness in biotite, implying the introduction of at least Fe, Mg, and K. In the second example the zones of hornblende enrichment imply the fixation of at least Fe, Mg, Ca, and Na. This local concentration and fixation of basic elements is a small scale example of the Fe-Mg " front " (Wegmann, 1935 ; Backlund, 1936, 1943 ; Reynolds, 1942, 1943, 1944), the importance of which has recently been emphasized by D. L. Reynolds (1947). The mechanism of aggregation and fixation of such diffusing materials has also recently been discussed by Holmes and Reynolds (1947).

It is worthy of notice that in the present study the basic front has been found to be more strongly developed in the second example owing to the more basic composition of the initial hornblende-biotite-pyroxene-schist from and within which it was formed. In consequence a greater supply of basic materials was displaced during granitization with the result that the hornblendic basic fronts eventually reached an ultrabasic composition.

Having established the sequence of formation of the various rock types within the two varieties of agmatite, and the mineralogical and chemical changes that took place during their development, it remains to consider the origin of the rocks which constituted the solid framework from which the agmatites were formed. In the first example transitions from the biotite-hornblende-schist to the neighbouring Moine rocks of sedimentary origin suggest that it likewise had a sedimentary origin. Mineralogically it resembles the biotite-hornblende-plagioclase-diabrochite, developed from diopside-hornfels of Silurian age in the Newry area, Northern Ireland (Reynolds, 1944, pp. 220–1), and this resemblance suggests that it may represent a chemically reconstituted calcareous shale or marl.

The hornblende-biotite-pyroxene-schist of the second example closely resembles the pyroxene-biotite-hornblende-schist described by Y. C. Cheng (1942) from the Bettyhill area in the north of Sutherland. It also resembles the widespread " Ach'uaine hybrids " described by Read (1925, pp. 45–50; 1926, pp. 154–166; 1931, pp. 165–172) from Sutherland. For these reasons the real nature of this rock and its relations to the various alteration products described in this paper are, I think, of sufficient interest to merit more detailed discussion.

As already shown in the earlier part of this paper the hornblende-biotite-pyroxene-schist represents a basic dyke that was emplaced before the period of Moine metamorphism that gave rise to the schistosity of the Moine rocks. The curious mineral composition of the hornblende-biotite-pyroxene-schist, however, in which sodic oligoclase and orthoclase are associated with a high percentage of mafic minerals makes it difficult to believe that it is an unaltered basic igneous rock. Cheng (1942, pp. 72–3) considered that the pyroxene-biotite-hornblende-schist of the Bettyhill area, together with the associated members of the hornblendic complex, represent hybrids that were produced by the " mixing of a granitic magma with an ultrabasic magma or with solid ultrabasic rocks " prior to the period of general migmatization in a way similar to that which had previously been suggested by Read (1926, pp. 154–166) for the " Ach'uaine hybrids ". Finding himself unable to distinguish the acid member of the supposed hybrids from the supposedly younger migmatites, Cheng suggested that the acid members responsible for the hybridization lost their identity when the rocks became subsequently migmatized. He further considered that the acid magma responsible for the hybridization was possibly the vanguard of the granites of the regional " injection-migmatization ". In making these suggestions Cheng attempted to separate what can now be seen to be one continuous process into two similar and indistinguishable stages.

The evidence furnished by the occurrence of hornblende-biotite-pyroxene-schist described in this paper is insufficient to establish the origin of the rock, but the writer will in a later communication present detailed evidence from other localities in the Rogart area to show that the hornblende-biotite-pyroxene-schist is itself a derivative from a member of the epidiorite–amphibolite suite. The hornblende-biotite-pyroxene-schist actually represents the initial stage of basification of a member of this suite, such a basification being complementary to the general migmatization of the surrounding rocks. The further evolution from hornblende-biotite-pyroxene-schist to hornblendite, dioritic rocks (members of the appinite suite) and migmatites has been described above. This evolution is to be attributed to one continuous process of solid diffusion (without the introduction of granite magma) in the course of which the development of migmatites involved the liberation of mafic constituents which were fixed in the basic rocks, thereby converting them to hornblendites.

The complete sequence of recognizable changes through which the basic rocks have passed is probably (1) basic schist → (2) hornblende-biotite-pyroxene-schist → (3) hornblendite → (4) appinitic rocks → (5) migmatite → (6) granodiorite. The study of these changes yields, in my opinion, an important clue towards the elucidation of the puzzling " Ach'uaine hybrids ".

Acknowledgments

The writer wishes to express his indebtedness to Dr. Doris L. Reynolds and Professor Arthur Holmes for their illuminating advice, encouragement, and constructive criticism given to him during this work, and his gratitude to the British Council for the award of a scholarship that enabled him to study in Britain.

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DESCRIPTION OF PLATE

FIG. 1.—A relict fragment of slightly granitized biotite-hornblende-schist in granodiorite at the road-side of Milton bank, north of Rogart Station. Note the basic rim developed from the schist at its margin against the granodiorite.

FIG. 2.—Agmatite developed from basic schist. Part of the rock surface illustrated in Text-fig. 2. Creag a' Bhata, north of Pittentrail, Rogart.

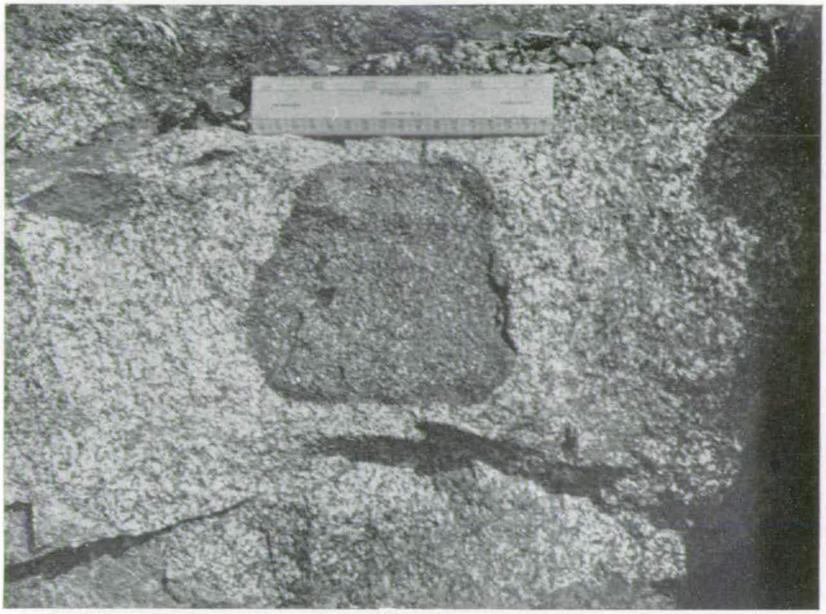


FIG. 1

FIG. 2

AGMATITE FROM THE ROGART AREA, SUTHERLANDSHIRE.

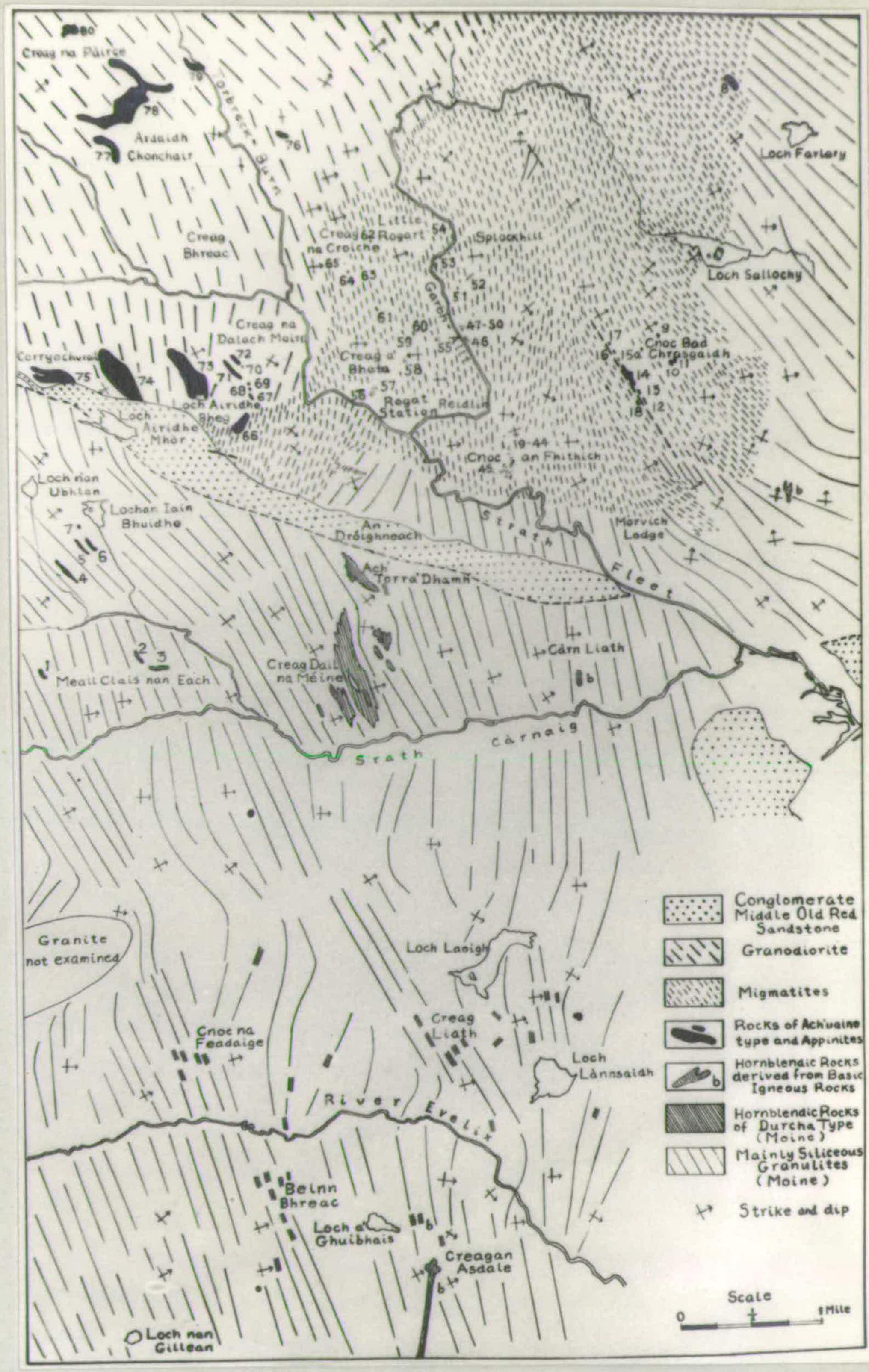


Fig. 1. Map of the Rogart area showing the chief rock-groups and their structural relationships.

Fig. 2.

Section across the large hornblendic sheets on the southern slope of Creag Dail na Moine. Dots = siliceous granulite; combined dashed lines and dots = striped and banded hornblendic rocks; line shading = hornblende-schist and amphibolite. For a detailed description see pp. 10-13.

Fig. 3.

Map showing the distribution of the basic bodies of Ach'uaine type at Cnoc an Fhithich, three-quarters of a mile E.S.E. of Rogart Station: Twelve inches to one mile.

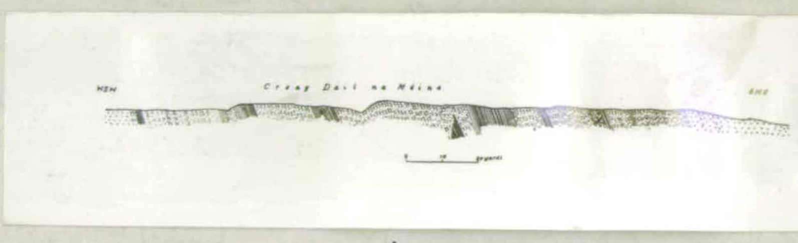

WNW
Creag Dail na Méine
ESE

Fig. 2.

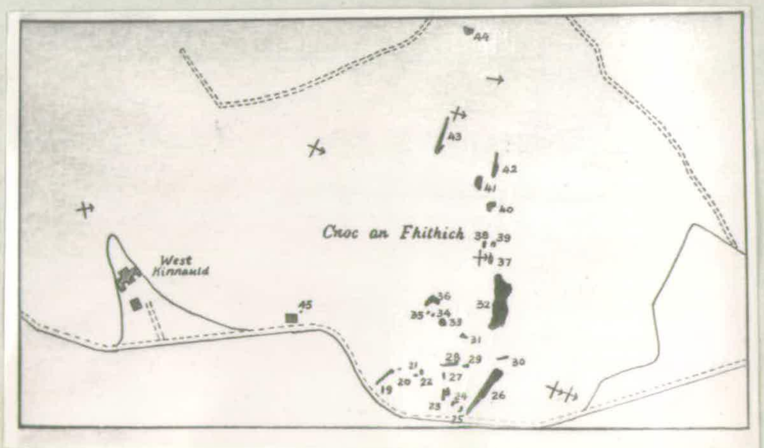

West Kinnauld
Cnoc an Fhithich
44
43
42
41
40
38 39
37
36
35 34
33
32
31
45
28 29
30
21
19 20 22
27
24
23
26
25

Fig. 3.

Fig. 4.

Networks of granitic veins in the rocks of Ach'uaine type which eventually lead to the formation of agmatite. Stippled = rocks of Ach'uaine type; criss-cross lines = appinitic rocks; white = granitic veins. Drawing of a rock face in basic mass No. 37, on Cnoc an Fhitich, three-quarters of a mile E.S.E. of Rogart Station.

Fig. 5.

Section across the southern end of the basic mass No. 74, north of Loch Airidhe Mhor, showing the distribution of different rock types. Close line shading - biotite-schist with little or no pyroxene and hornblende; stippled - melasyenodiorites, with dashed lines indicating the schistosity dependent on the parallel orientation of the biotite flakes; ^ -pattern - shonkinite, with here and there schistosity shown by dashed lines. The schistosity is dependent on the parallel orientation of the biotite flakes; criss-cross lines - appinite; heavy dashed lines - granodiorite. For a detailed description see pp. 30-32.

Fig. 6.

A petrological sketch of a group of small rock slabs at the south-eastern end of the basic mass No. 72, south-west of Dalmore Quarry. The sketch shows the development of a narrow belt of hornblendite (small scale basic front; solid black) between the granodiorite (white, with potash feldspar porphyroblasts shown as small squares) and rocks of Ach'uaine type (dots). For a detailed description see pp. 33-34.

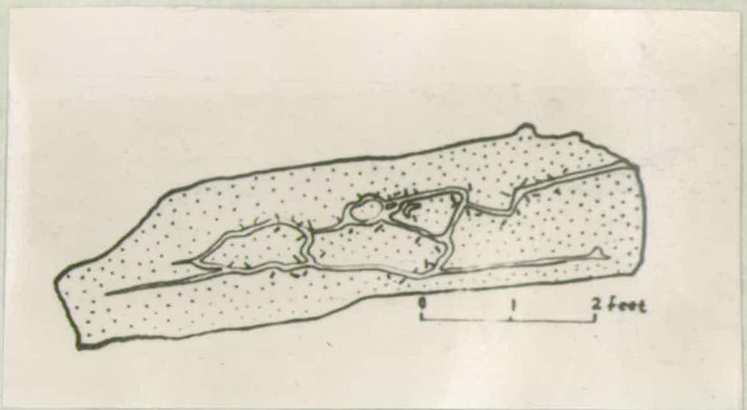


Fig. 4.

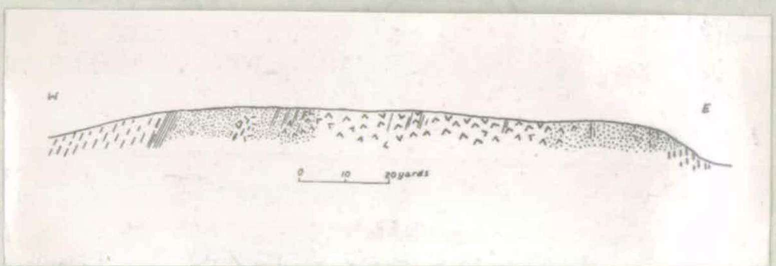


Fig. 5.

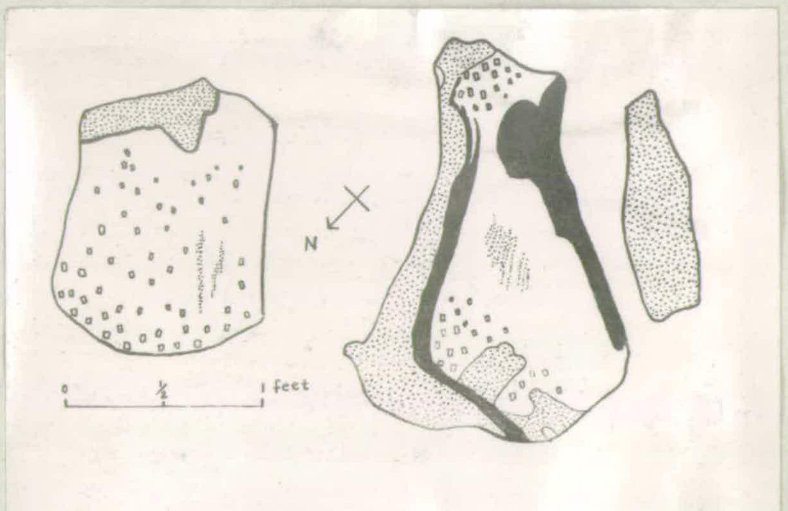


Fig. 6.

Fig. 7.

Section across the northern portion of the basic mass No. 78, showing its relation to the surrounding granodiorite. North of Ardaidh Choncahair, Rogart. For a detailed description see pp. 35-36.

Fig. 8.

A sketch map of the basic mass No. 79, east of Creag na Pairce, showing the distribution of different rock types. Short dashed lines = relict hornblendic Moine rocks; dots = mela-syenodiorites; dense dots = feldspathic hornblendite; criss-cross lines = appinite; heavy dashed lines = granodiorite. For a detailed description see pp. 36-37.

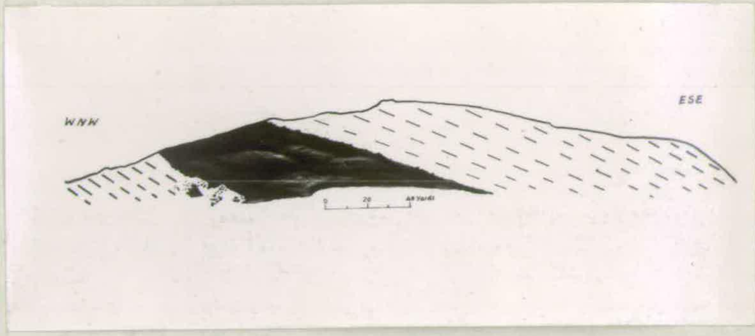


Fig. 7.

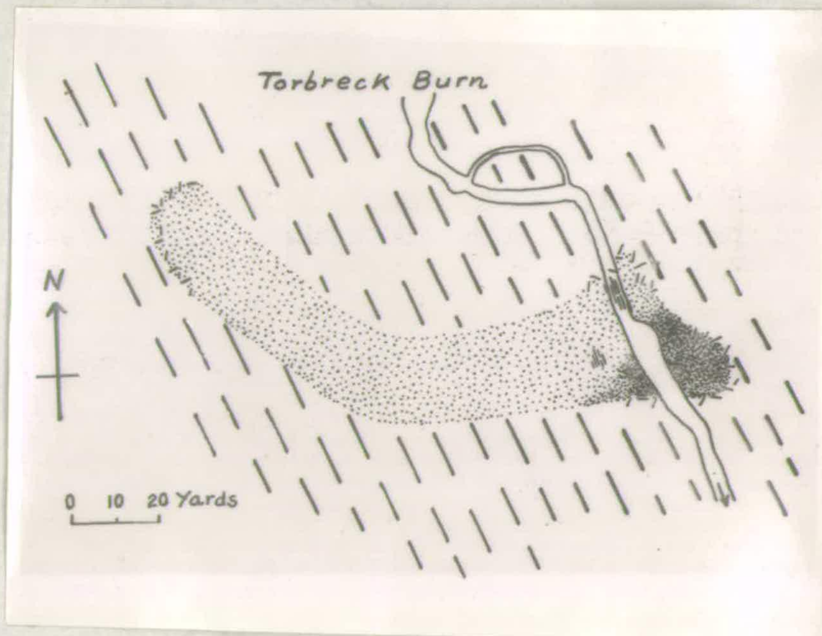
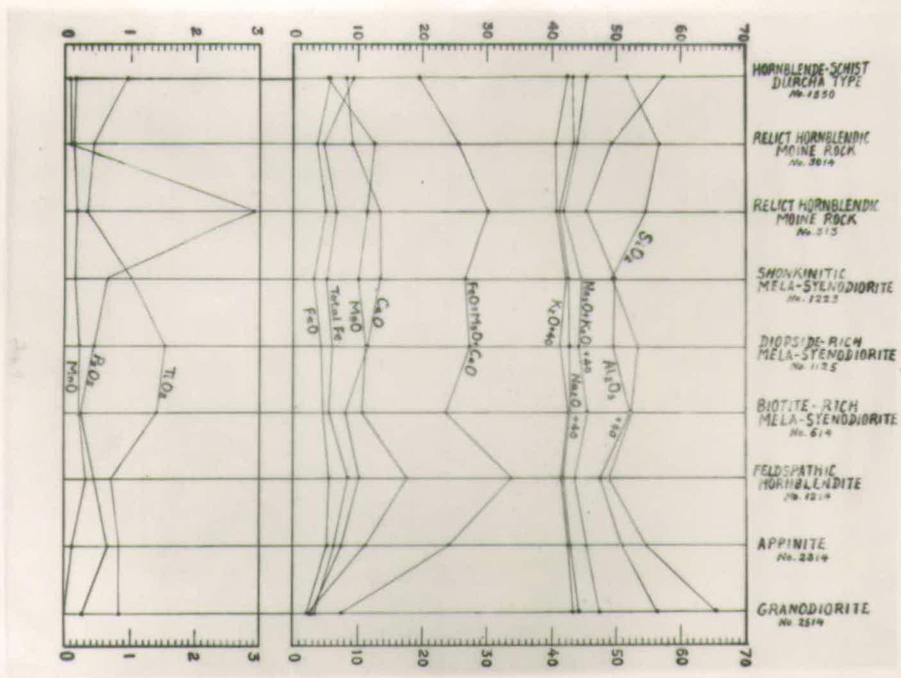


Fig. 8.

Fig. 9.

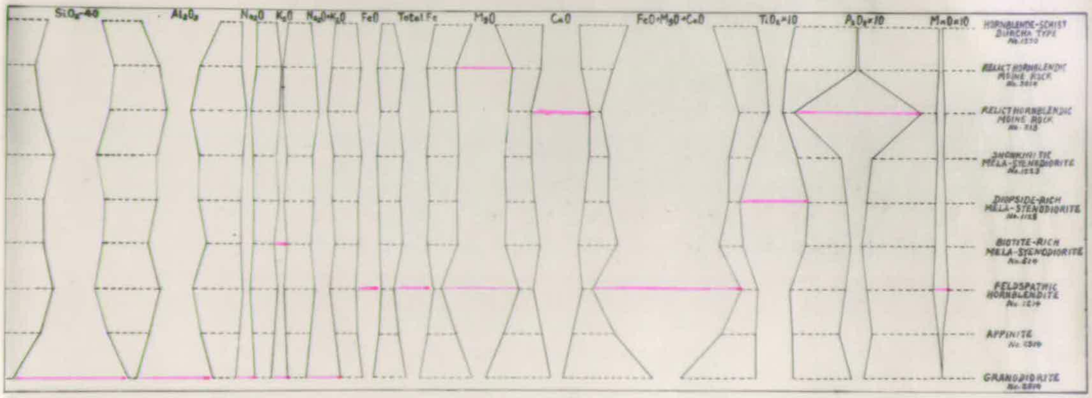
Variation diagram of the rock series ranging from hornblende-schist of Durcha Type to granodiorite of the Rogart area. The analyses of the different rock members are plotted at equal intervals according to their sequence of formation.



HORNBLENDE-SCHIST
DURCHA TYPE
RELICT HORNBLENDIC
MOINE ROCK
RELICT HORNBLENDIC
MOINE ROCK
SHONKINITIC
MELA-SYENODIORITE
DIOPSIDE-RICH
MELA-SYENODIORITE
BIOTITE-RICH
MELA-SYENODIORITE
FELDSPATHIC
HORNBLENDITE
APPINITE
GRANODIORITE

Fig. 10.

Diagram showing the relative abundances of the various oxides within the various members of the rock series that ranges from hormblende-schist to the Rogart granodiorite. The red lines indicate 'geochemical culminations'.



SiO_2-40
Al_2O_3
Na_2O
K_2O
Na_2O+K_2O
FeO
Total Fe
MgO
CaO
FeO+MgO+CaO
TiO_2×10
P_2O_5×10
MnO×10
HORNBLENDE-SCHIST DURCHA TYPE
RELICT HORNBLENDIC MOINE ROCK
RELICT HORNBLENDIC MOINE ROCK
SHONKINITIC MELA-SYENODIORITE
DIOPSIDE-RICH MELA-SYENODIORITE
BIOTITE-RICH MELA-SYENODIORITE
FELDSPATHIC HORNBLENDITE
APPINITE
GRANODIORITE

Fig. 11.

von Wolff diagram of the rock series ranging from hornblende-schist of Durcha Type to the Rogart granodiorite. The numbers refer to the chemical analyses of the rocks recorded in Table IX. L = feldspars, M = saturated melanocrats, Q. = quartz, Leu= Leucite and O = olivine.

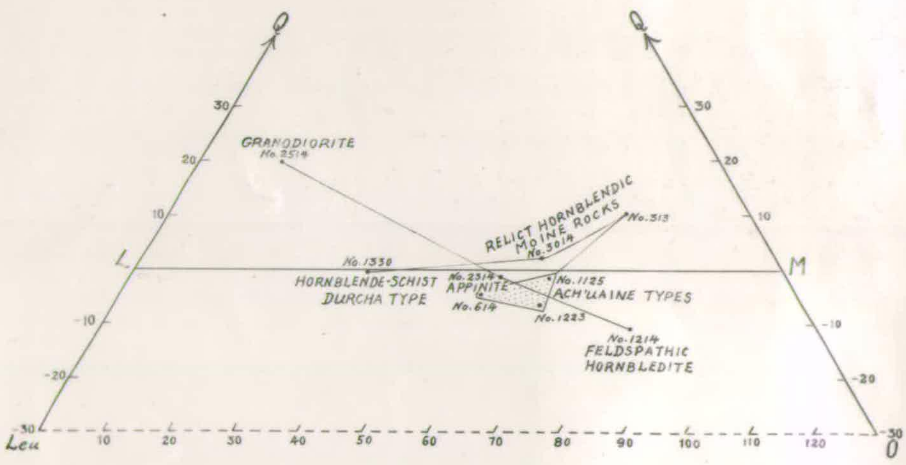
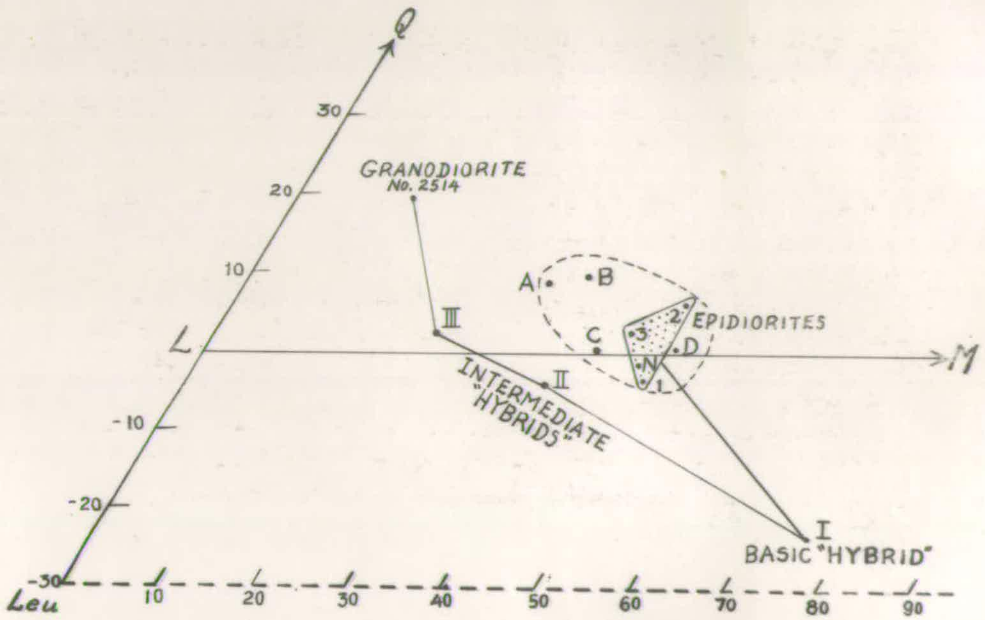

Q
Q
30
20
10
L
M
-10
-20
-30
GRANODIORITE
No.2514
RELICT HORNBLENDIC
MOINE ROCKS
No.3014
No.313
No.1330
HORNBLENDE-SCHIST
DURCHA TYPE
No.2314
APPINITE
No.1125
ACH'UAINE TYPES
No.614
No.1223
No.1214
FELDSPATHIC
HORNBLEDITE
Leu
10
20
30
40
50
60
70
80
90
100
110
120
O

Fig. 12.

von Wolff diagram illustrating the relation between the so-called 'hybrid' rocks of the Ach'uaine area and the epidiorites. The field for normal basalts, dolerites and norites, indicated by the dashed line enclosing A, B, C, D and N, is shown for comparison with the epidiorites. A.= Kennedy's (1933) olivine-basalt "magma type" for the British Tertiary province; B = Kennedy's tholeiitic "magma type" for the British Tertiary province; C = Daly's average for all basalts; D = Daly's average for plateau basalts; and N = Read's (1923) average of 44 chemical analyses of rocks designated norite, taken from Washington's 'Chemical Analyses of Igneous Rocks', U.S. Geol. Surv. P.P. 99, 1917.



Q
30
20
10
L
-10
-20
-30
Leu
10
20
30
40
50
60
70
80
90
M
GRANODIORITE
No. 2514
III
II
I
INTERMEDIATE
"HYBRIDS"
BASIC "HYBRID"
A
B
C
D
N
1
2
3
EPIDIORITES

Fig. 13.

Hornblende-schist (No. 1330) from the large hornblendic mass at the summit of Creag Dail na Méine. The foliation is dependent on the parallelism of prisms of hornblende. Ordinary light x 20.

Fig. 14.

Feldspathic portion of a hornblende-schist (No. 529) from the smaller hornblendic mass S.W. of the summit of Creag Dail na Méine, showing the coating of pyroxene (Py) to hornblende (H). Ordinary light x 26.

Fig. 15.

Hornblende-schist (No. 3130) from the hornblendic band west of Ach' Torra' Dhamh, showing the poikiloblastic development of pyroxene (Py) with enclosed hornblende. Ordinary light x 26.

Fig. 16.

Striped hornblendic rock (No. 22729x) from 1130 yds. N. by E. of the summit of Creag Dail na Méine, showing the alteration of narrow melanocratic bands rich in epidote (right hand side of the field) and hornblende (dark), and leucocratic bands rich in plagioclase and quartz. Ordinary light x 24.

Fig. 13.

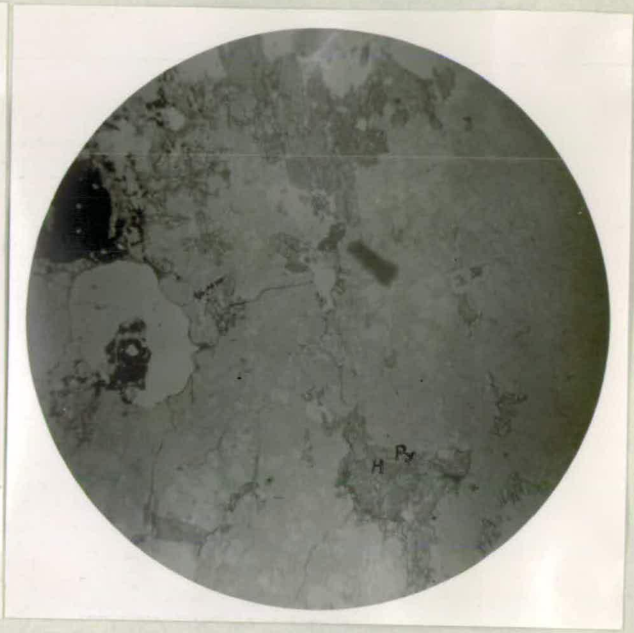


Fig. 14.

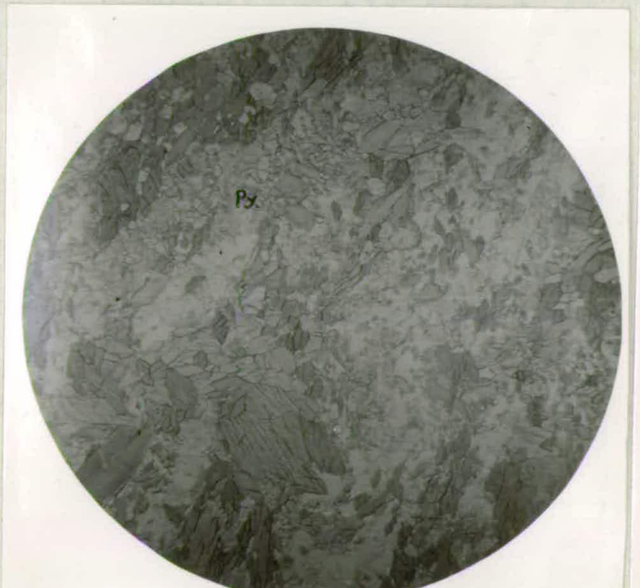


Fig. 15.

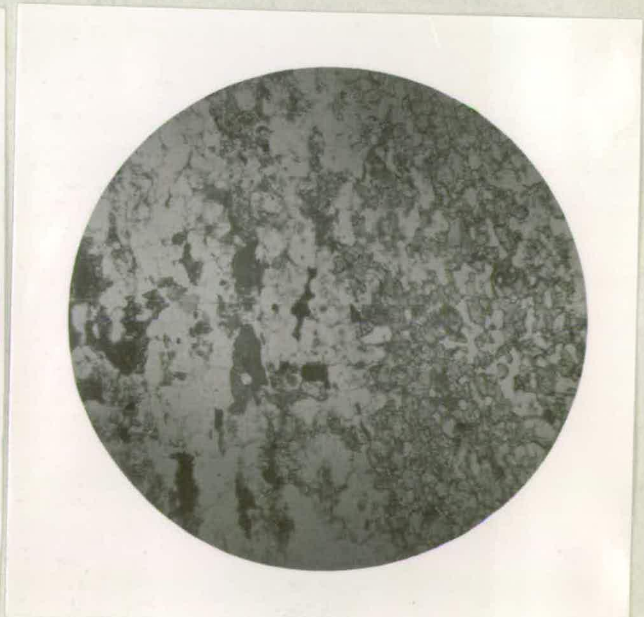


Fig. 16.

Fig. 17.

Ep idiorite (No. 68) from a small epidiorite body one-third of a mile north of the summit of Creagan Asdale, showing the association of hornblende (dark grey) and feldspar (grey). Ordinary light x 24.

Fig. 18.

Epidiorite (No. 22796x) from the middle portion of the Creagan Asdale epidiorite dyke, half a mile S. by E. of Loch a Ghiubhais, showing the ophitic relationship between the hornblendic and feldspathic areas. Ordinary light x 24.

Fig. 19.

Garnet-bearing hornblende-schist (No. 78) from the marginal part of the Creagan Asdale epidiorite dyke, half a mile S. by E. of Loch a' Ghiubhais. Ordinary light x 21.

Fig. 20.

Relict hornblendic rock (No. 3014) from the basic mass No. 79 (see Fig. 8), east of Creag na Pairce, showing the association of light greenish coloured hornblende and feldspar. Ordinary light x 22.

Fig. 17.

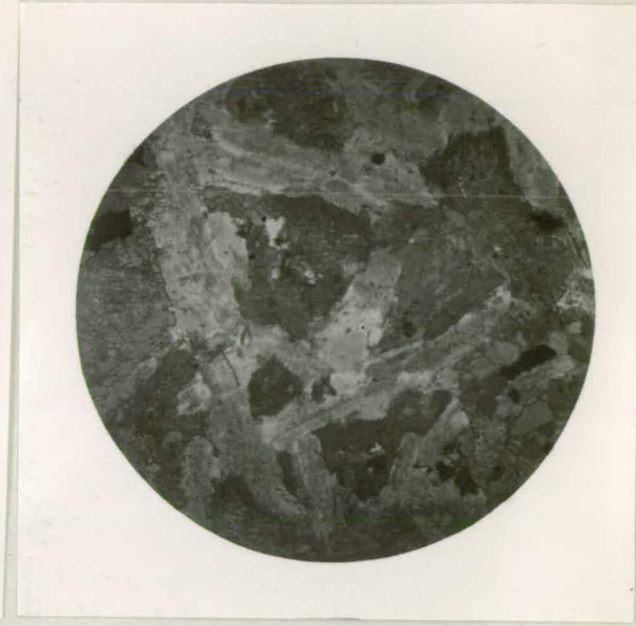


Fig. 18.

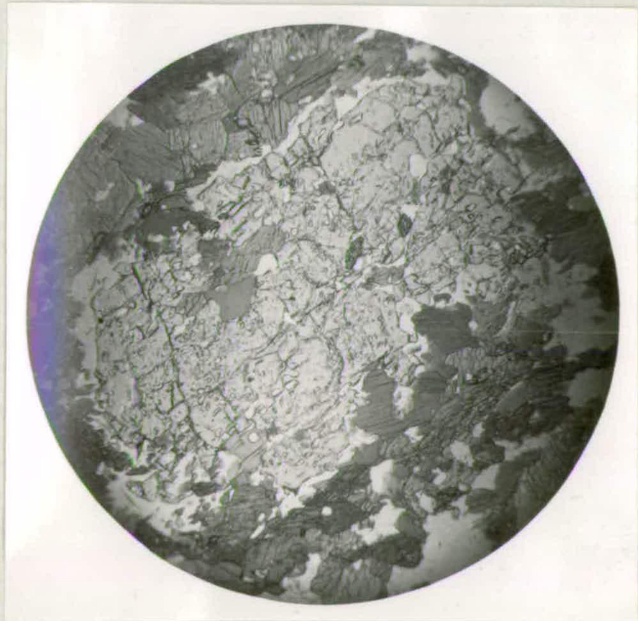


Fig. 19.

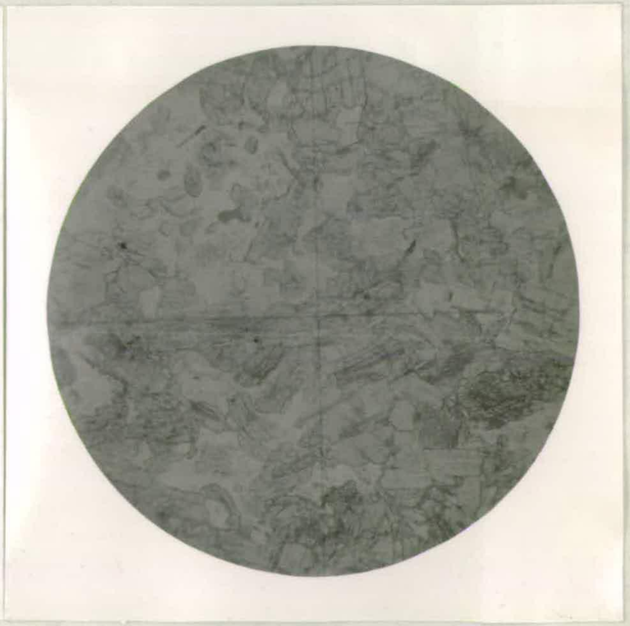


Fig. 20.

Fig. 21.

Relict hornblende rock (no. 313) from the eastern portion of the basic mass No. 10, on the summit of Cnoc Bad a' Chrasgaidh. The field illustrates a pyroxene-rich patch in the hornblendic rock. The pyroxene crystals are enclosed in the feldspar. A wedge-shaped crystal of sphene appears on the right-hand side of the field, while numerous prisms of apatite can be seen towards the middle. Ordinary light x 22.

Fig. 22.

Relict hornblendic rock (No. 313) from the eastern portion of the basic mass No. 10, on the summit of Cnoc Bad a' Chrasgaidh, showing the replacement relationship between the hornblende (H) and pyroxene (Py). A skeletal-shaped sphene appears in the lower left portion of the field, while small prisms of apatite appear towards the middle. Ordinary light x 24. (For a detailed description of the replacement relationship between hornblende and pyroxene see pp. 67-68).

Fig. 23.

Shonkinite (No. 2124) from the basic mass No. 74, north of Loch Airidhe Mhòr illustrating the dependence of foliation on the parallelism of biotite flakes. The colourless areas are chiefly orthoclase, while the greyish patches are diopside. Ordinary light x 24.

Fig. 24.

Shonkinite (No. 10) from the middle portion of the basic mass No. 74, north of Loch Airidhe Mhòr, showing the association of biotite, diopside and orthoclase. The foliation is dependent on the sub-parallel alighment of the biotite individuals. Ordinary light x 24.

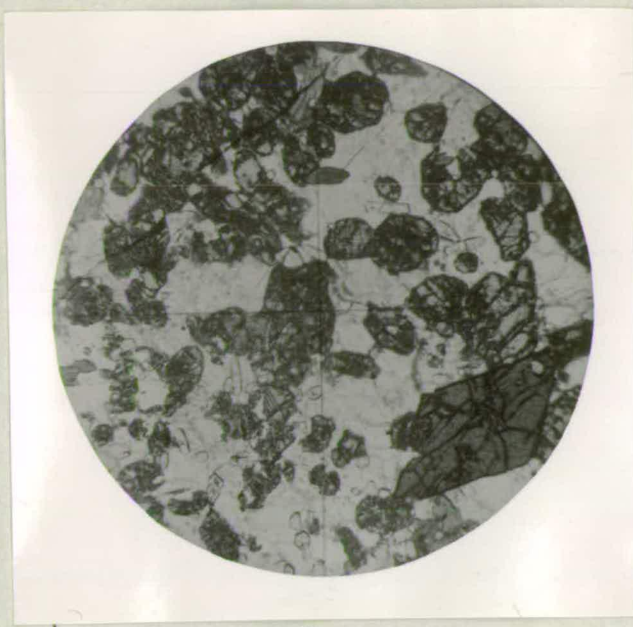


Fig. 21.

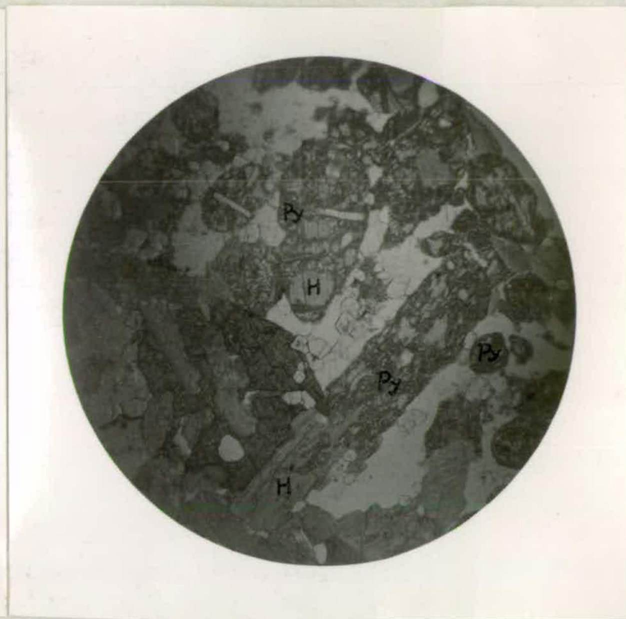


Fig. 22.

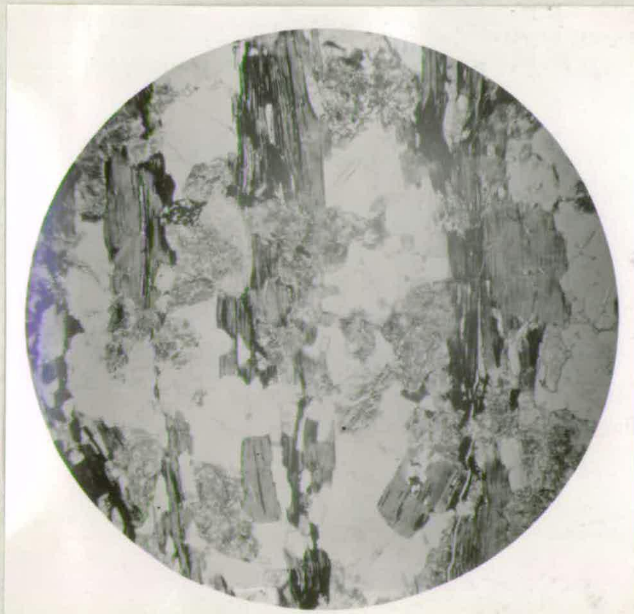


Fig. 23.

Fig. 24.

Fig. 25.

Shonkinitic mela-syenodiorite (No. 1223) from the middle portion of the basic mass No. 75, E.N.E. of Corryachvrail. The field is occupied by a single biotite individual and prisms of diopside. It illustrates the poikiloblastic growth of the biotite, which tends to weave through and enclose the diopside. Ordinary light x 24.

Fig. 26.

Shonkinite (No. 1022) from the middle portion of the basic mass No. 74, north of Loch Airidhe Mhòr, showing the association of chocolate-brown coloured biotite, diopside and feldspar. The large biotite flakes seen in the lower left-hand portion of the field poikiloblastically enclose numerous prisms of diopside. Large apatite crystals appear in the upper middle portion of the field. Ordinary light x 24.

Fig. 27.

Shonkinite (No. 1722) from the basic mass No. 74, north of Loch Airidhe Mhòr, showing a large perthitic orthoclase individual which enclosed numerous inclusions of diopside. Hornblende appears in the upper middle portion of the field (dark patchy grey). Crossed nicols x 24.

Fig. 28.

Shonkinite(No. 1022)from the middle portion of the basic mass No. 74, north of Loch Airidhe Mhòr, showing a typical association of diopside, hornblende and feldspar. The wedge-shaped crystal towards the centre of the field is sphene, and hornblende appears in both the lower middle and the upper right portions of the field. The colourless areas are chiefly perthitic orthoclase. Ordinary light x 24.

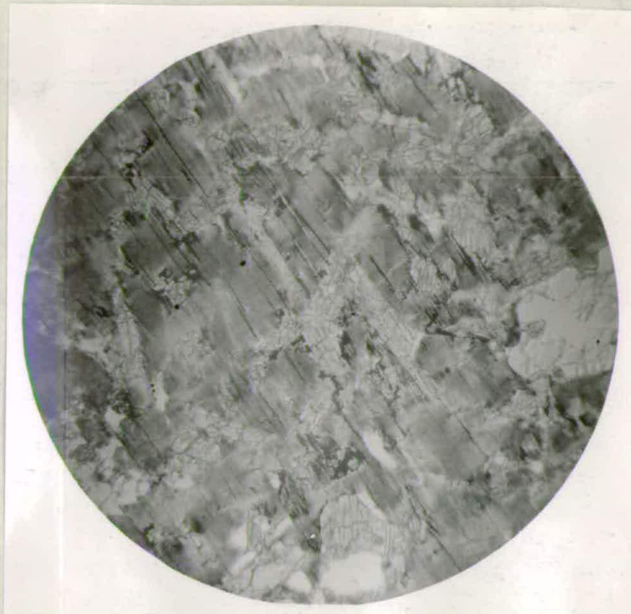


Fig. 25.

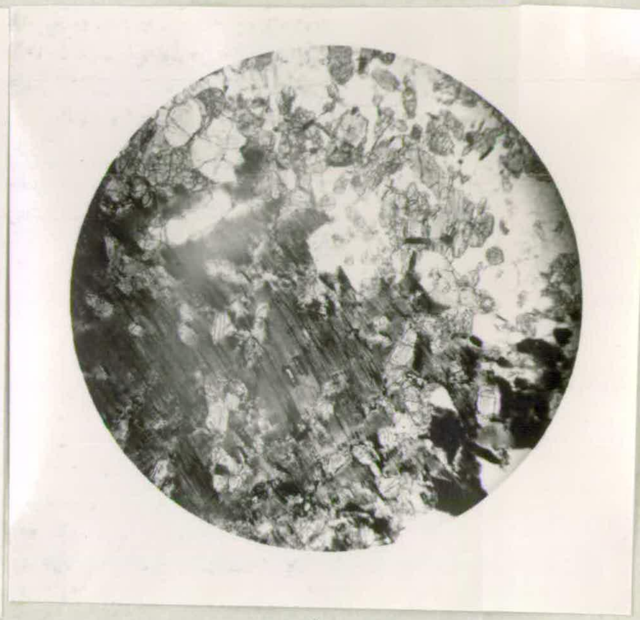


Fig. 26.

Fig. 27.

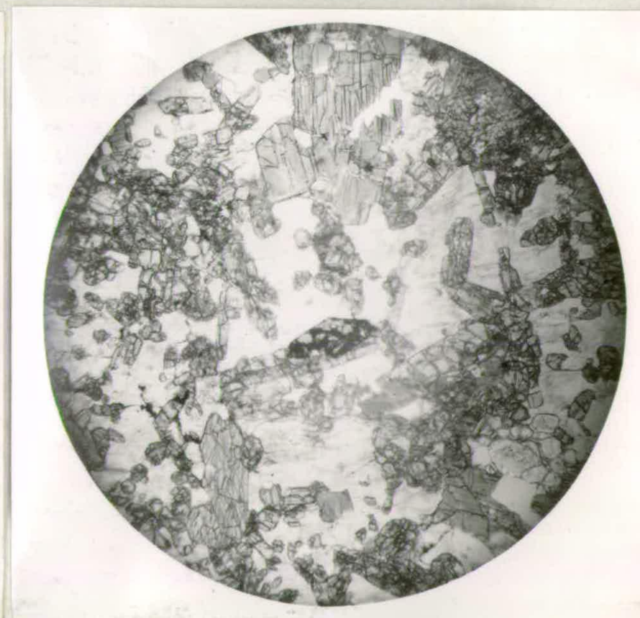


Fig. 28.

<u>Fig. 29.</u>

Shonkinitic mela-syenodiorite (No. 1223) from the middle portion of the basic mass No. 75, E.N.E. of Corryachvrail, showing the haphazard arrangement of diopside within the feldspar (light grey). The small dark flakes are biotite. Ordinary light x 24.

<u>Fig. 30</u>

Shonkinite (No. 21) from the western margin of the basic mass No. 10, on the summit of Cnoc Bad a' Chrasgaidh, showing the association of diopside and feldspar (orthoclase) in a basic variety of the shonkinite. Ordinary light x 24.

<u>Fig. 31.</u>

Diopside-rich mela-syenodiorite (No. 1125) from the northern margin of the basic mass No. 78, north of Ardaidh Chonachair, showing the association of diopside, biotite, hornblende (H) and feldspar (colourless). Sphene is seen in the upper middle portion of the field. Ordinary light x 24.

<u>Fig. 32.</u>

Diopside-rich mela-syenodiorite (No. 1125) from the northern margin of the basic mass No. 78, north of Ardaidh Chonachair, showing the association of diopside and twinned oligoclase, which in part encloses the diopside. Crossed nicols x 24.

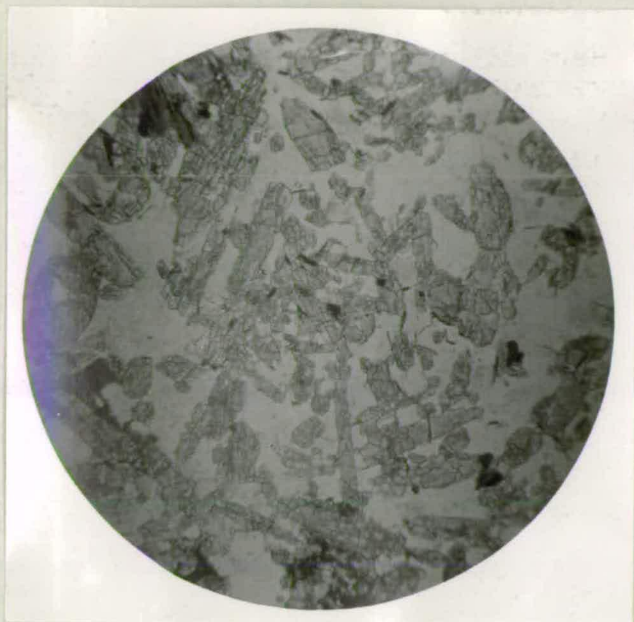


Fig. 29.

Fig. 30.

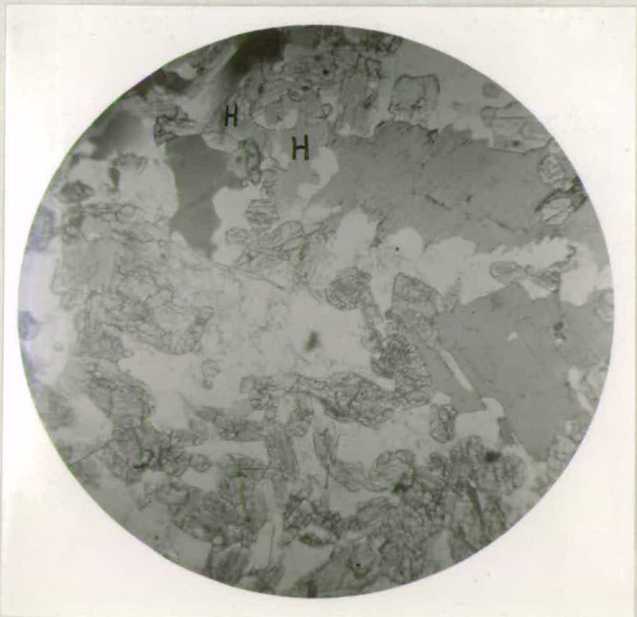


Fig. 31.

Fig. 32.

Fig. 33.

Diopside-rich mela-syenodiorite (No. 1225) from the northern margin of the basic mass No. 78, north of Ardaidh Chonachair, showing part of a skeletal-shaped hornblende sieved with feldspar and diopside. The isolated portions of the hornblende are in optical continuity. Sphene granules can be seen in the upper middle portion of the field. Ordinary light x 24.

Fig. 34.

Biotite-rich mela-syenodiorite (No. 614) from the basic mass No. 79, east of Creag na Pairce. This is a typical field and shows (a) A large subhedral crystal of oligoclase with irregular areas of orthoclase (dark grey) enclosed. The orthoclase areas are all in optical continuity and also show the same optical orientation as a larger crystal of orthoclase outside the oligoclase (lower right-hand margin of the field. (b) A large oligoclase crystal enclosing diopside prisms, biotite flakes and subordinary amounts of sphene, apatite and hornblende. The dark areas towards the upper right and lower left quadrants of the field are biotite, while the dark area of the middle right-hand margin of the field i is an emphy space in the rock section. Crossed nicols x 24.

Fig. 35.

Biotite-rich mela-syenodiorite (No. 614) from the basic mass No. 79, east of Creag na Pairce, showing the association of biotite and diopside and feldspar. In the middle portion of the field there are two large poikiloblastic biotite individuals, one (dark areas) with a basal section and the other nearly perpendicular to it. The enclosure of diopside in the large biotite flakes is again very well displayed. Orthite (Or) appears as dark greyish grains towards the middle of the field. Ordinary light x 24.

Fig. 36.

Biotite-rich mela-syenodiorite (No. 716) from basic mass No. 7, S.W. of Lochan Iain Bhuidhe, showing the association of biotite, apatite and feldspar. Apatite, in this particular specimen makes up about 35 per cent of the rock. The apatite prisms have a dark interior portion crowded with minute rods and bleb-like inclusions. The biotite appears dark. An orthite crystal can be recognised in the upper right quadrand of the field.

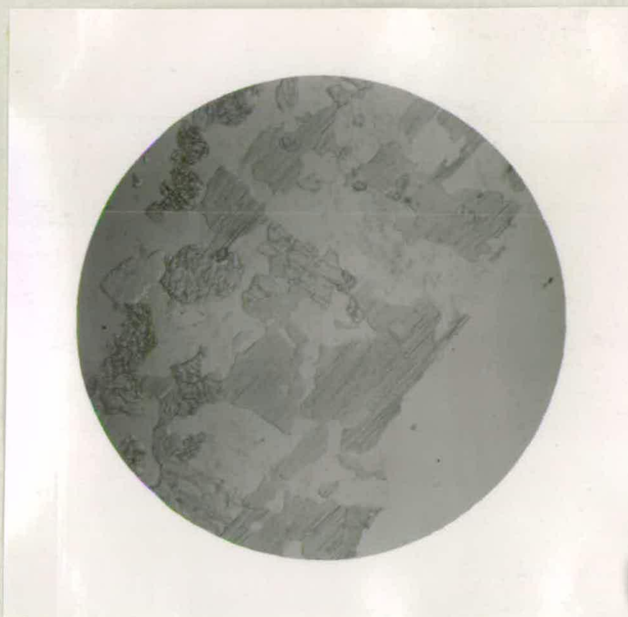


Fig. 33.

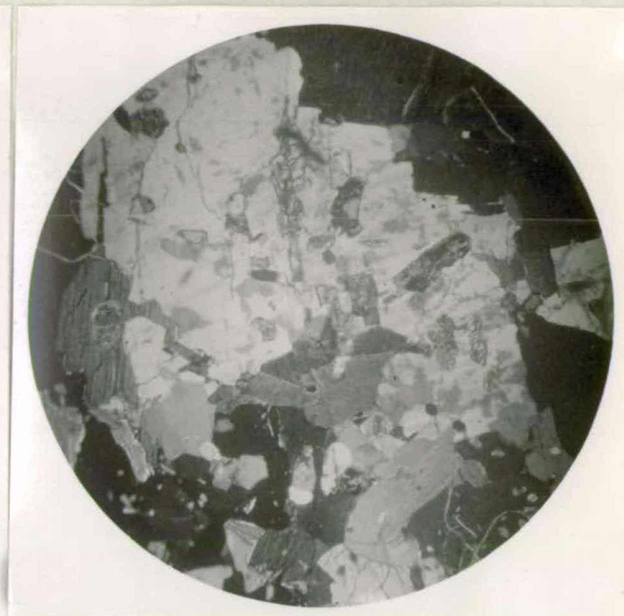
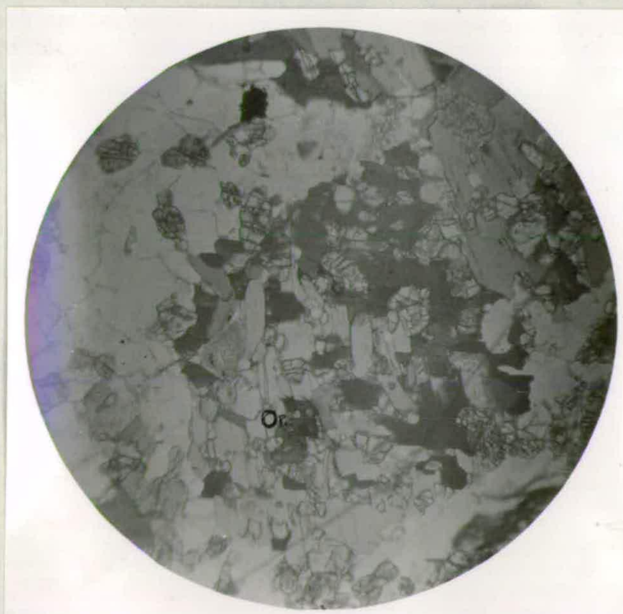


Fig. 34



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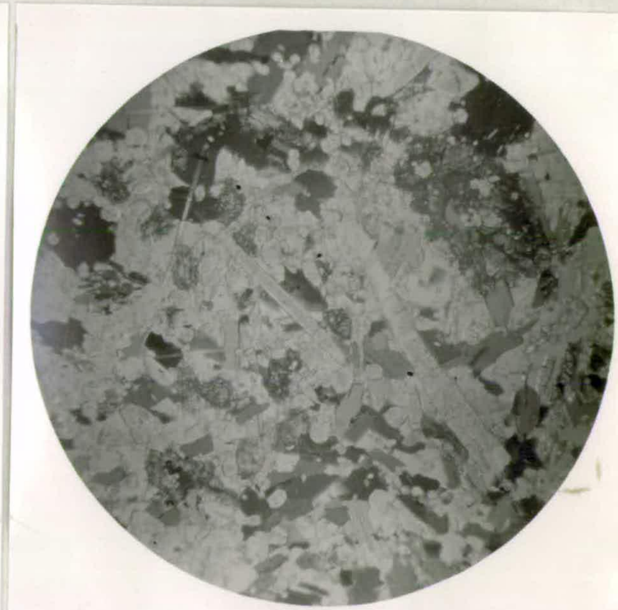


Fig. 36.

Fig. 37.

Biotite-rich mela-syenodiorite (No. 19) from the western portion of the basic mass No. 10, on the summit of Cnoc Bad a' Chrasgaidh, showing a typical association of biotite, diopside, hornblende and feldspar. The hornblende at the middle right-hand side of the field contains numerous inclusions of diopside grains.

Fig. 38.

Biotite-rich mela-syenodiorite (No. 19) from the western portion of the basic mass No. 10, on the summit of Cnoc Bad a' Chrasgaidh, showing numerous areas of orthoclase (grey) distributed through large oligoclase individuals (colourless) in a anti-perthitic pattern. The orthoclase areas show straight margins which are parallel to the vertical boundaries (010 and 100) of the large oligoclase, but their terminations are jagged. The orthoclase areas are all in optical continuity. The dark area towards the top of the field is a basal section of biotite, while diopside (grey) and hornblende (dark grey) can be seen in the lower right-hand corner of the field. Crossed nicols x 24.

Fig. 39.

Biotite-rich mela-syenodiorite (No. 19) from the western portion of the basic mass No. 10, on the summit of Cnoc Bad a' Chrasgaidh, showing the association of biotite, diopside, and feldspar. The oligoclase stretching across the middle of the field shows numerous anti-perthitic areas of orthoclase in the mian part of the crystal, which are all in optical continuity amongst themselves and with a larger crystal of orthoclase outside the oligoclase (right hand side of the field). Crossed nicols x 24.

Fig. /

Fig. 40.

Biotite-rich mela-syenodiorite (No. 19). An enlarged view of part of the same field as No. 39 showing the contact between the orthoclase and the oligoclase, and the uniform optical orientation between the orthoclase crystal and the orthoclase areas of the anti-perthite. Crossed nicols x 39.

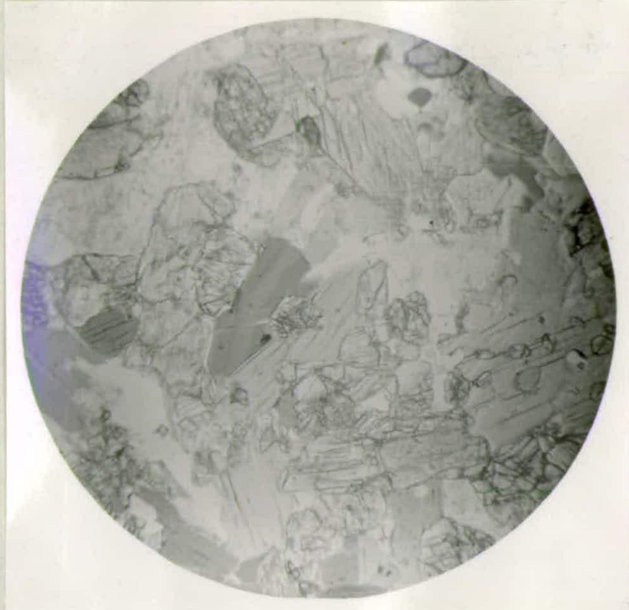


Fig. 37.

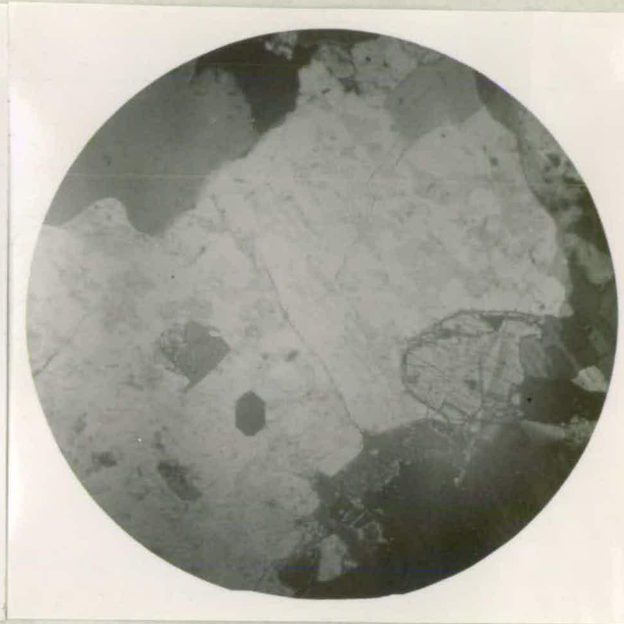


Fig. 38.

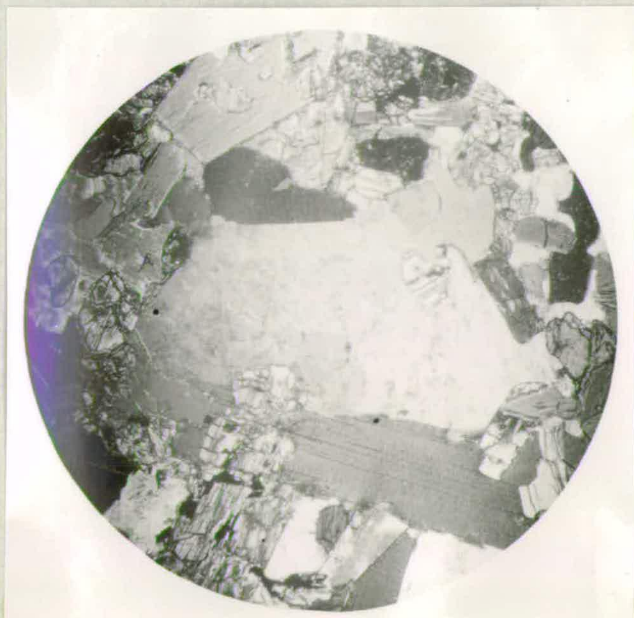


Fig. 39.

Fig. 40.

Fig. 41.

Biotite-rich mela-syenodiorite (No. 19) from the western portion of the basic mass No. 10, on the summit of Cnoc Bad a' Chrasgaidh, showing the contact relationship between orthoclase (grey) and the oligoclase (colourless). Note that in the larger orthoclase individuals there are perthitic patches which have the same optical orientation as a larger crystal of oligoclase outside with which some of the patches are continuous. Note also the saw-like junction between the biotite (dark) and the feldspar. Crossed nicols x 24.

Fig. 42.

Biotite-rich melasyenodiorite (No. 22) from the western portion of the basic mass No. 10, on the summit of Cnoc Bad a' Chrasgaidh, showing the association of large biotite flakes poikiloblastically enclosing hornblende (middle left-hand side of field) and diopside. Numerous crystals of apatite are seen in the lower left quadrant of the field. Ordinary light x 24.

Fig. 43.

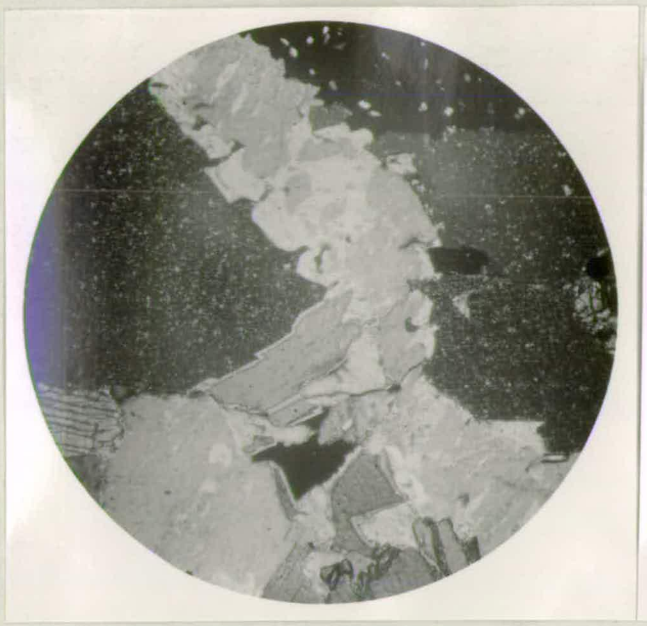
Feldspathic hornblendite (No. 1214) from the south-eastern corner of the basic mass No. 79, east of Creag na Pairce, showing a large hornblende individual, with inclusions of stout crystals of apatite (upper right and middle lower margins of field), irregular areas of feldspar (towards the middle of the field) and grains of diopside (stretching from the top to the lower left-hand margin of the field). Note the trains of light greenish coloured hornblende surrounding the diopside inclusions. A large biotite flake occupies the N.W. margin of the field. Ordinary light x 24.

Fig. 44.

Feldspathic hornblendite (No. 1214) from the south-western corner of the basic mass No. 79, east of Creag na Pairce showing dactylitic outgrowths from biotite (middle left quadrant of the field) and hornblende (upper left quadrant of the field)

where /

where these minerals adjoin feldspar. Note the fibrous aggregates of light coloured actinolitic amphibole in the feldspar and at the marginal part of the large hornblende crystal. Ordinary light x 24.



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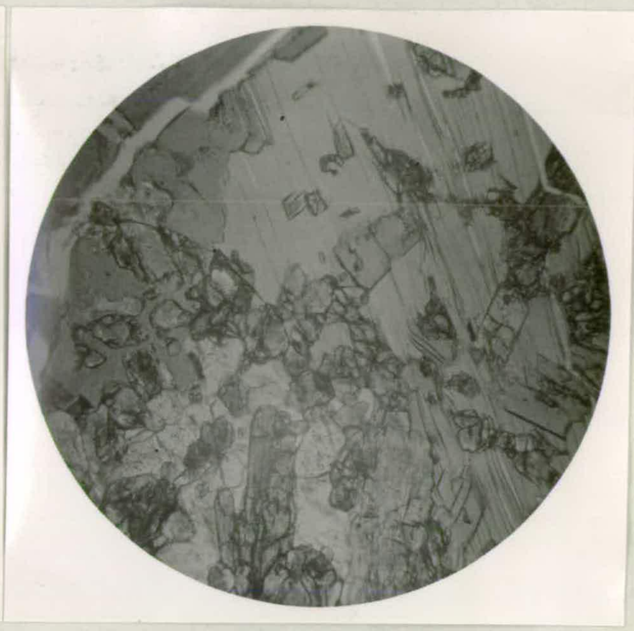

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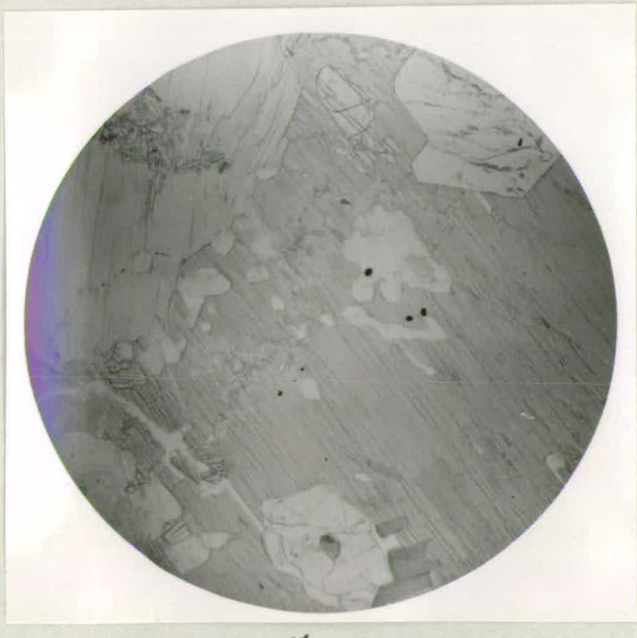

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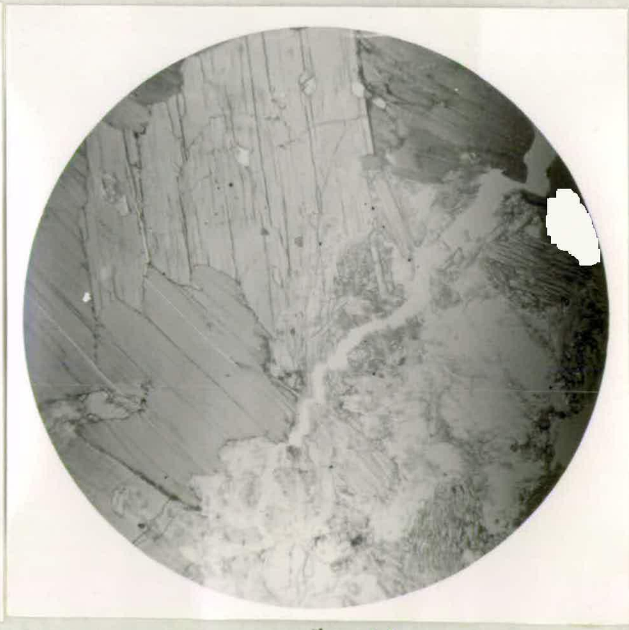


Fig. 44.

Fig. 45.

Feldspathic hornblendite (No. 1114) from the south-western corner of the basic mass No. 79, east of Creag na Pairce, showing how fibrous actinolitic amphibole (lower left quadrant of the field) grades into the ordinary green hornblende. Ordinary light x 24.

Fig. 46.

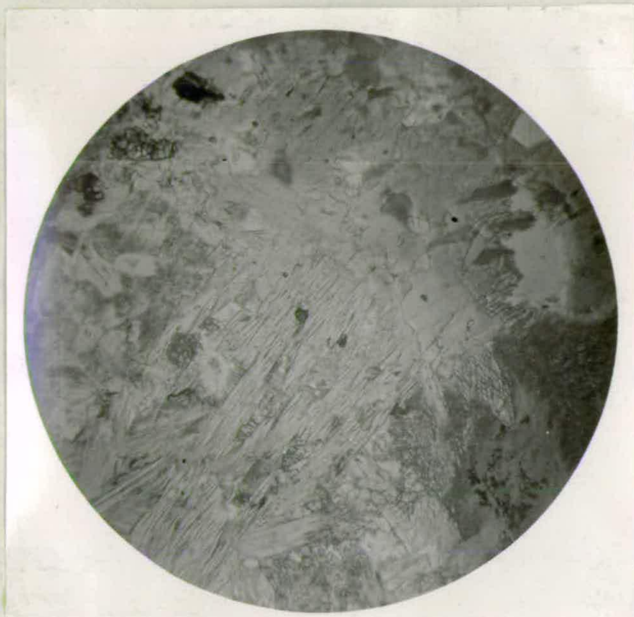
Pyroxene-rich patch in the feldspathic hornblendite (No. 814) from the south-western corner of the basic mass No. 79, showing a diopside crystal with excellent sieve texture. Ordinary light x 24.

Fig. 47.

Appinite (No. 2314) from the northern margin of the basic mass No. 79 east of Creag na Pairce, showing (a) the sieve texture of the large hornblende crystals (lower quadrant of the field); and (b) the irregular contacts between oligoclase (P) and orthoclase (O). The plagioclase perthitic lamellae and patches of plagioclase within the Orthoclase (O) are physically continuous within the oligoclase (P). Crossed nicols x 24.

Fig. 48.

Appinite (No. 2314) from the northern margin of the basic mass No. 79, east of Creag na Pairce, showing hornblende with sieve texture. Biotite inclusions in the hornblende appear dark. The hexagonal crystals to the right of the middle of the field are apatite. Ordinary light x 24.



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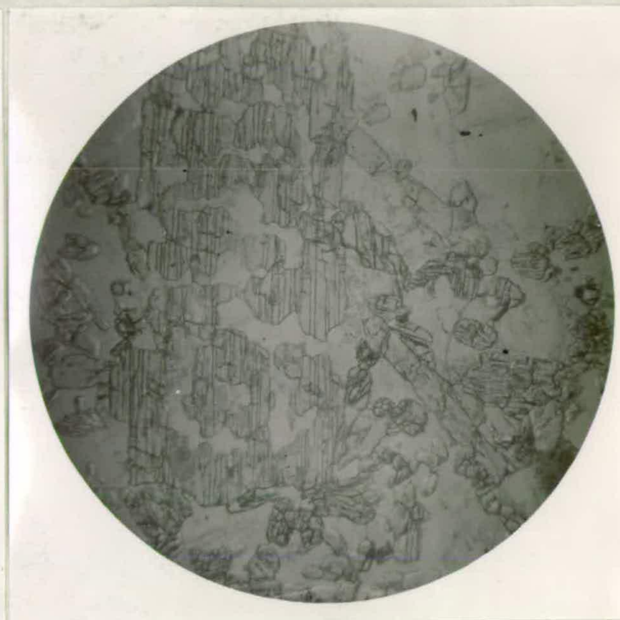

Fig. 46.

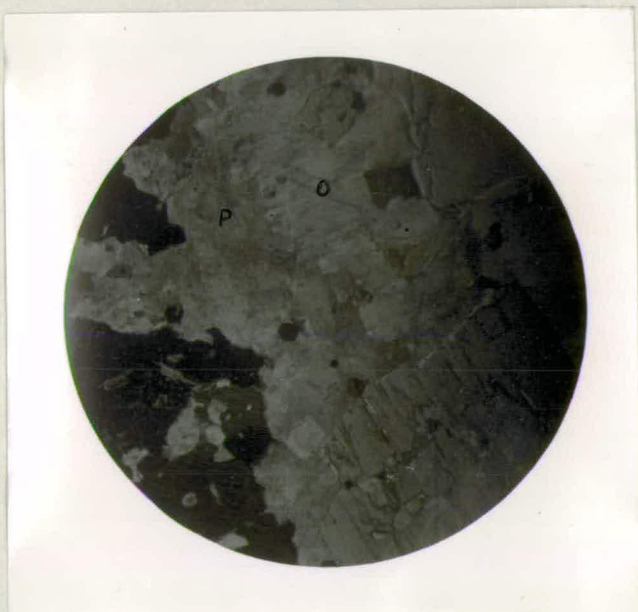

Fig. 47.

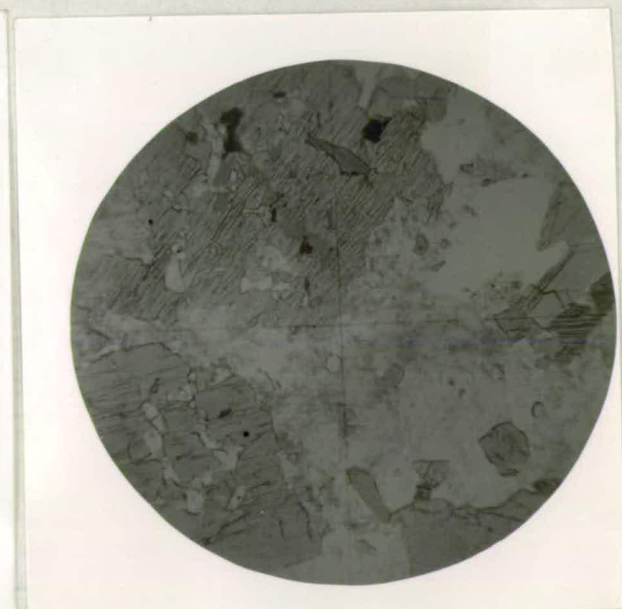

Fig. 48.

Fig. 49.

Appinite (No. 2314) from the northern margin of the basic mass No. 79, east of Creag na Pairce, showing the parallel intergrowth of biotite (B) and hornblende (H). The white coloured areas towards the lower right and upper left quadrant of the field are empty spaces in the section. Ordinary light x 24.

Fig. 50.

Appinite (No. 4) from the south-eastern margin of the basic mass No. 79 east of Creag na Pairce, showing parallel intergrowth of skeletal hornblende with biotite (dark). Numerous apatite crystals appear in the right-hand side of the field. Ordinary light x 24.

Fig. 51.

Appinite (No. 3012) from the basic mass No. 14 south-west of Cnoc Bad a' Chrasgaidh, showing the development of skeletal biotite flakes in hornblende (basal section). The different parts of the biotite are in optical continuity. Ordinary light x 24.

Fig. 52.

Appinite (No. 4) from the south-eastern margin of the basic mass No. 79, east of Creag na Pairce, showing the irregular contact between the orthoclase (white) and the oligoclase (grey). The dark areas in the field are empty spaces in the thin section. Crossed nicols x 24.

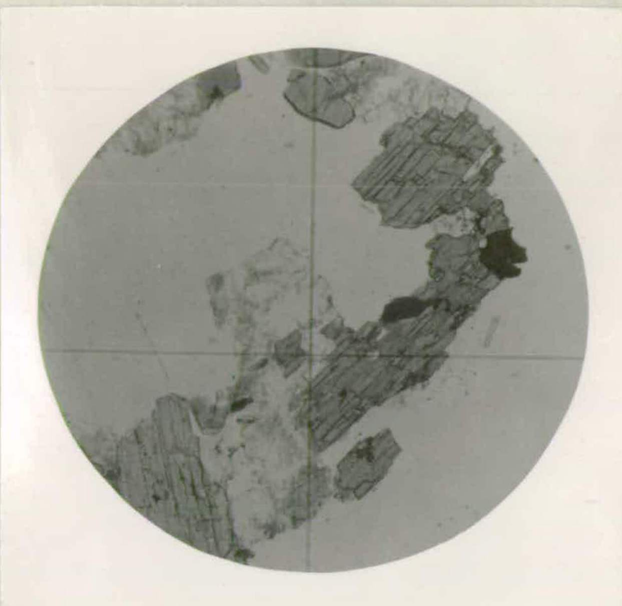

Fig. 49.

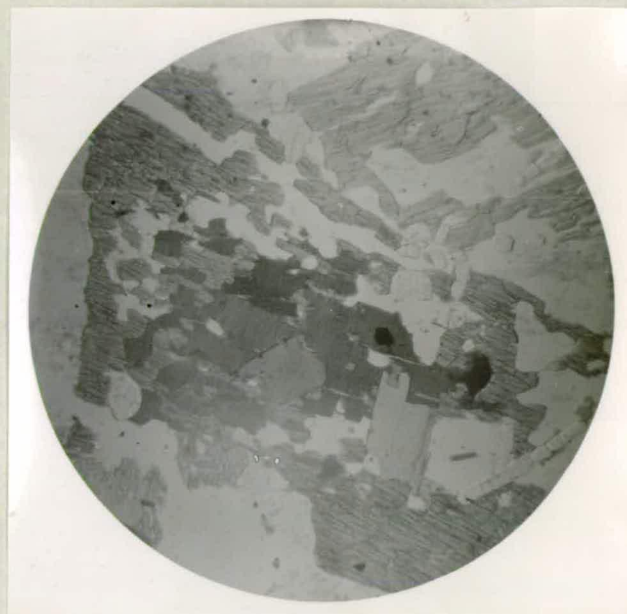

Fig. 50.

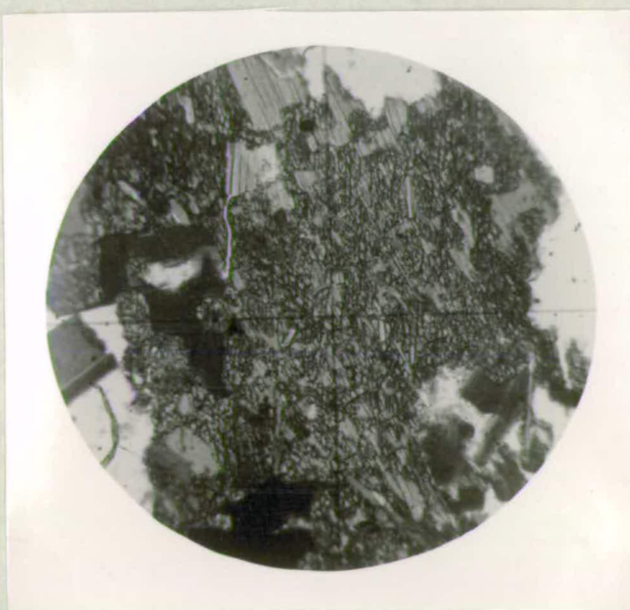

Fig. 51.

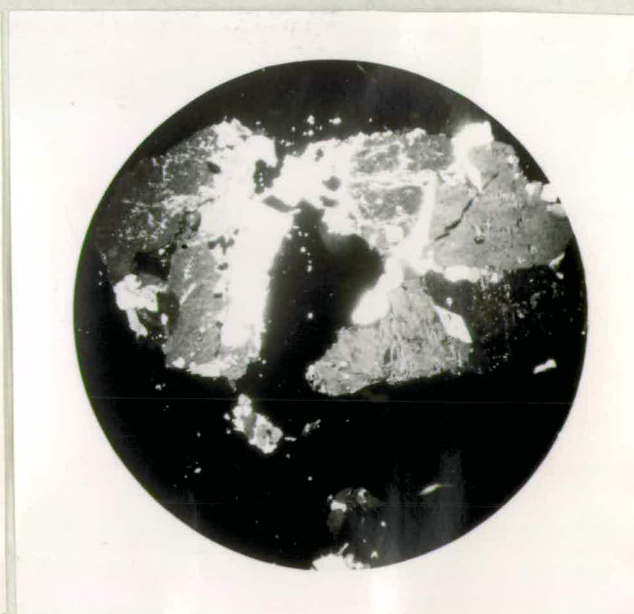

Fig. 52.

Fig. 53.

Diorite (No. 2414) from the northern corner of the basic mass No. 79, east of Creag na Pairce, showing (a) the curving contact between oligoclase (dark and twinned) and orthoclase (on the right-hand side of the field); and (b) the sericitised core and clear margin of the oligoclase. Hornblende appears at the top of the field. Crossed nicols x 24.

Fig. 54.

Diorite (No. 2414) from the northern corner of the basic mass No. 79, east of Creag na Pairce, showing (a) the contact between orthoclase (grey) and oligoclase (upper right quadrant of the field); and (b) the physical and optical continuity of the perthitic lamellae in the orthoclase with the larger oligoclase outside the orthoclase. The large wedge-shaped crystals towards the N.W. and S.E. of the field are sphene. The crystals (grey) with prismatic cleavages are hornblende. The dark area towards the lower left-hand margin of the field is an empty space in the thin section Crossed nicols x 24.

Fig. 55.

Granodiorite (No. 5) from 2 yds. outside the south-eastern margin of the basic mass No. 79, east of Creag na Pairce, showing (a) the dentated outlines of the contact between plagioclase (left quadrant of the field) and orthoclase (light grey, right hand of the field); (b) the sericitised central portion and the clear margin of the oligoclase, and (c) myrmekite texture appearing in one of the protruded portion of the oligoclase. Crossed nicols x 24.

Fig. 56.

Granodiorite (No. 2514) from 1 yd. outside the northern corner of the basic mass No. 79, east of Creag na Pairce, showing (a) the sinuous and dentated outlines of the contact between orthoclase (O) and oligoclase (P); and (b) small isolated oligoclase areas towards the middle of the field, within the orthoclase which may have been originally connected with the large oligoclase individual on the left. Crossed nicols x 24.

Fig. 53.

Fig. 54

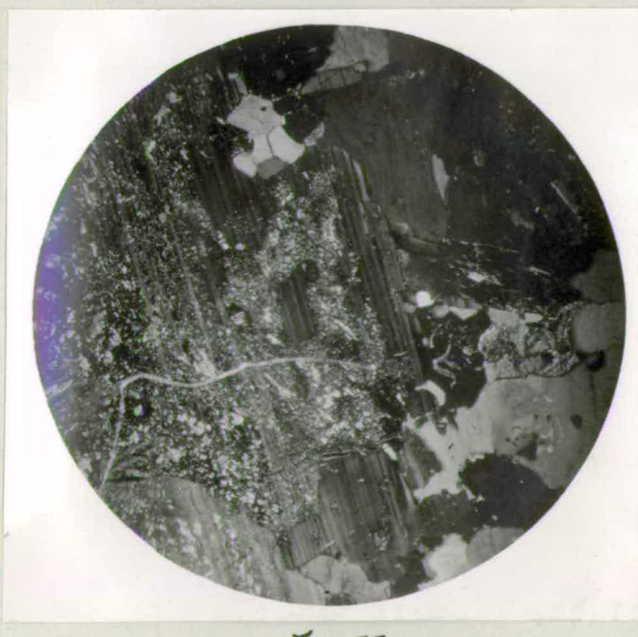

Fig. 55.

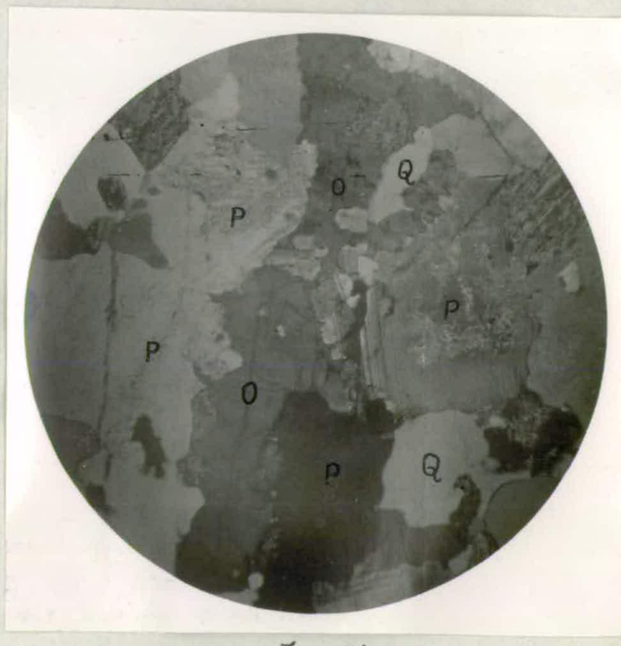

Fig. 56.

Fig. 57.

Granodiorite (No. 428) from outside the basic mass No. 58, east of the summit of Creag a' Bhata, showing (a) isolated islands of oligoclase (light grey) within orthoclase (dark grey in optical continuity with the larger oligoclase individuals outside the orthoclase; and (b) the irregular contact between orthoclase and oligoclase. The large variegated crystal in the N.W. of the field is chloritised biotite. Crossed nicols x 24.

Fig. 58.

Granodiorite (No. 2514) from 1 yd. outside the northern margin of the basic mass No. 79, east of Creag na Pairce, showing a large porphyroblast of orthoclase surrounded by a mantle of oligoclase. Note (a) the myrmekitic encroachment of oligoclase upon orthoclase; (b) the sericitised oligoclase relics in the wider portions of the plagioclase perthitic lamellae; and (c) the bright margins of sodic oligoclase seen at the contacts between oligoclase inclusions and orthoclase. Inclusions of biotite appear in the orthoclase near the S.E. margin of the field. Crossed nicols x 24.

Fig. 59.

Granodiorite (No. 44a) from inside the basic mass No. 58, east of the summit of Creag a Bhata, showing petaloid shaped myrmekite at the contact between oligoclase (dark and twinned) and orthoclase (on the upper and right side of the field). The oligoclase of the myrmekite is in uniform optical orientation with the oligoclase to which it is attached. Note that the quartz vermicules at the lower margin of the myrmekite (marked), continue into the adjoining orthoclase. Quartz appears at the bottom and N.W. margins of the field. Crossed nicols x 24.

Fig. 60.

Granodiorite (No. 44a) from inside the basic mass No. 58, east of the summit of Creag a' Bhata, showing an isolated plagioclase crystal (enclosed in orthoclase) which shows a marginal part of clear and more sodic oligoclase against the orthoclase (the marginal and main part of the oligoclase do not extinguish together). On the upper /

upper right hand corner of the same crystal myrmekite appears. The myrmekite of the S.W. corner of the field has been described above (No. 58). Crossed nicols x 24.

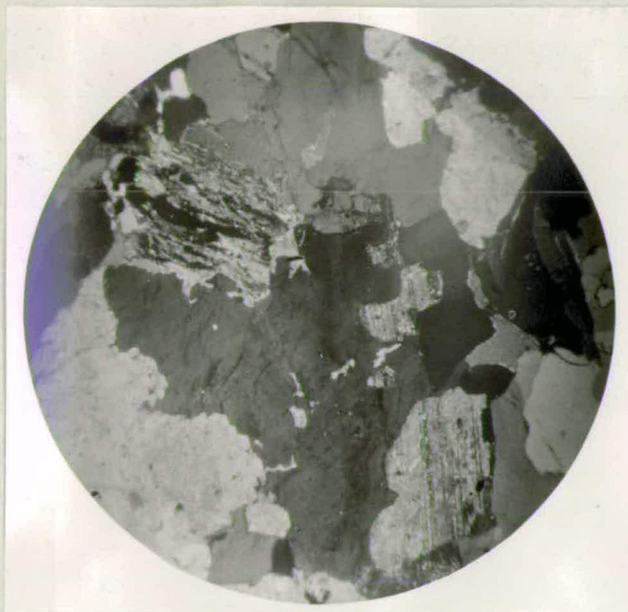

Fig. 57.

Fig. 58.

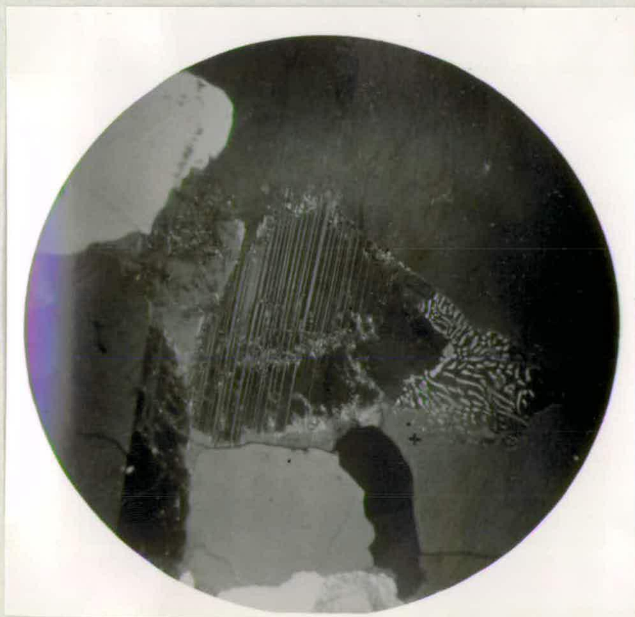

Fig. 59.

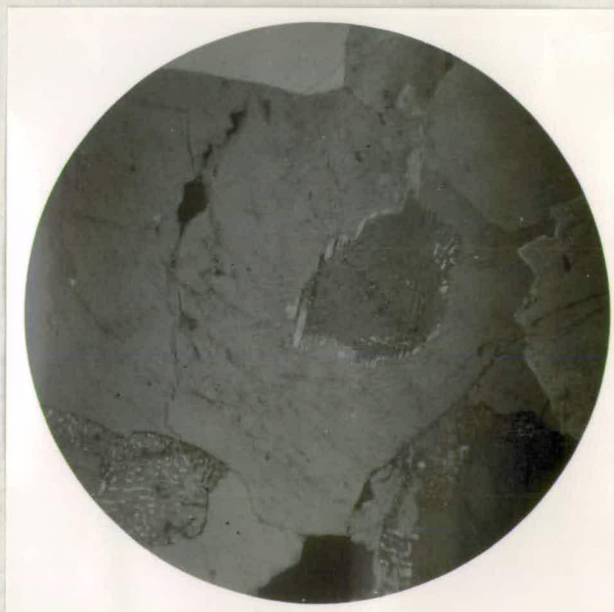

Fig. 60.

Fig. 61.

Granodiorite (No. 213) from 1 yd. outside the basic mass No. 10, on the summit of Cnoc Bad a' Chmasgaidh, showing the sinuous outlines of the contact between the quartz (colourless) and feldspar (grey). Note the quartz blebs enclosed in the neighbouring feldspar. Crossed nicols x 24.

Fig. 62.

Diopside-rich mela-syenodiorite (No. 825) from the northern margin of the large basic mass No. 78, north of Ardaidh Chonachair, showing a tabular crystal of orthoclase with perthitic lamellae in the middle of the field; it encloses an irregular patch of oligoclase and hornblende. Note that the perthitic lamellae of plagioclase are in part linked with the oligoclase patch. Crossed nicols x 24.

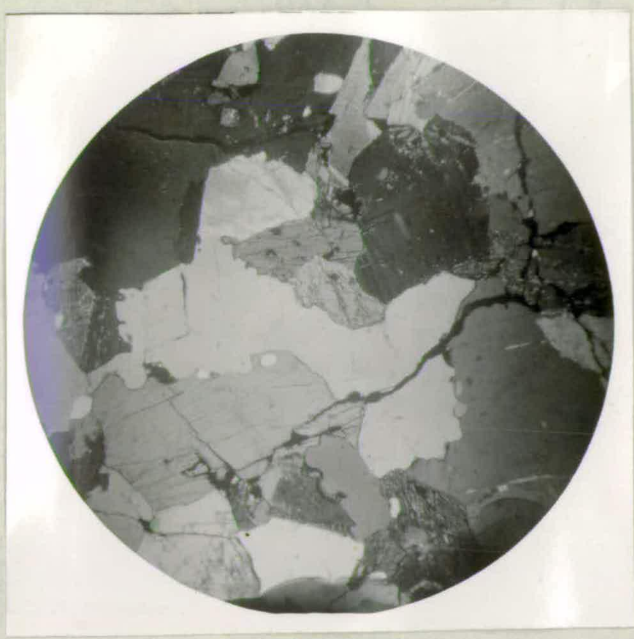

Fig. 61.

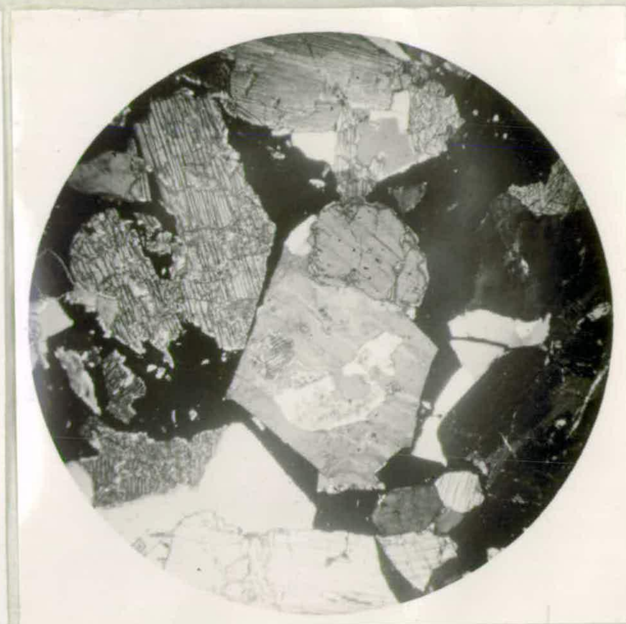

Fig. 62.

Fig. 63.

Westernmost portions of the section shown in Fig. 5, showing the contact between the granodiorite and the basic mass of Ach'uaine type (No. 74), North of Loch Airidhe Mhòr, two miles W.N.W. of Rogart Station.

Fig. 64.

Central portion of the section shown in Fig. 7, showing the upper and lower contact of the basic mass No. 78, north of Ardaidh Chonachair, Rogart.

Fig. 63.

Fig. 64.

Fig. 65.

Weathered surface of shonkinite showing the development in the dark matrix of white feldspathic spots which are surrounded by hornblende prisms. Basic mass No. 73, north of Loch Airidhe Bheg, one and a half miles west of Rogart Station.

Fig. 66.

Horizontal surface of shonkinite, showing clusters of white feldspathic spots standing out in relief from the rest of the rock as a result of differential wathering. Basic mass No. 73, north of Airidhe Bheg, one and a half miles of Rogart Station.

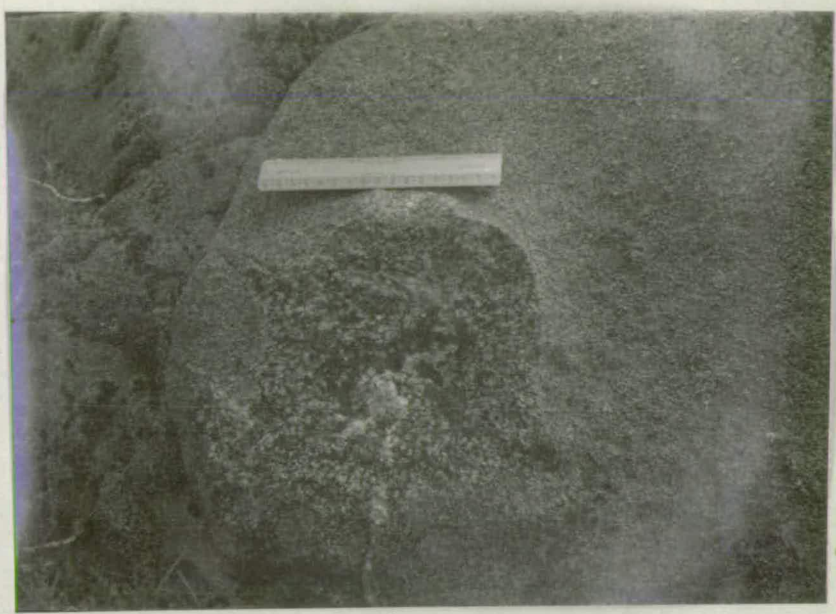

Fig. 65.

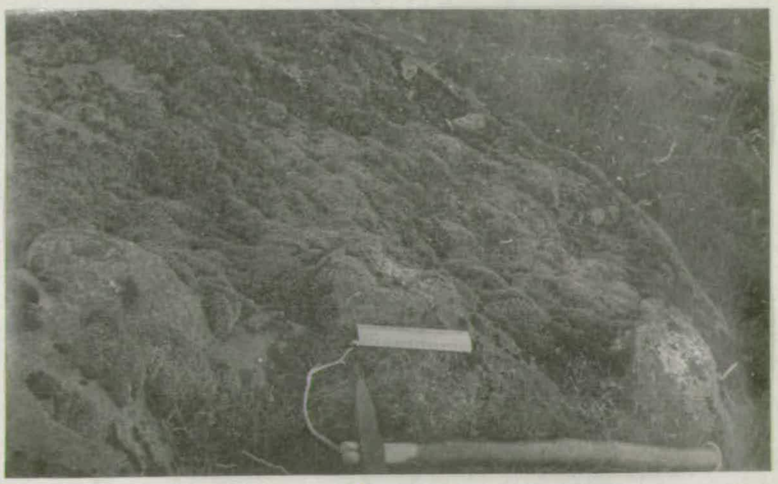

Fig. 66.

Fig. 67.

Creag na Dalach Moire, a mile north-west of Rogart Station. The Rogart Granite Quarries (Dalmore Quarry) are at the south-west side of the summit.

Fig. 68.

A general view of the Rogart Granite Quarries (Dalmore Quarry), a mile north-west of the Rogart Station. These quarries were worked by an Aberdeen firm about forty years ago; later they abandened the work beacuse of the difficulty of extracting homogeneous blocks free from relics of pre-existing rocks.

X = where Fig. 69 was taken
Y = where Fig. 70 was taken

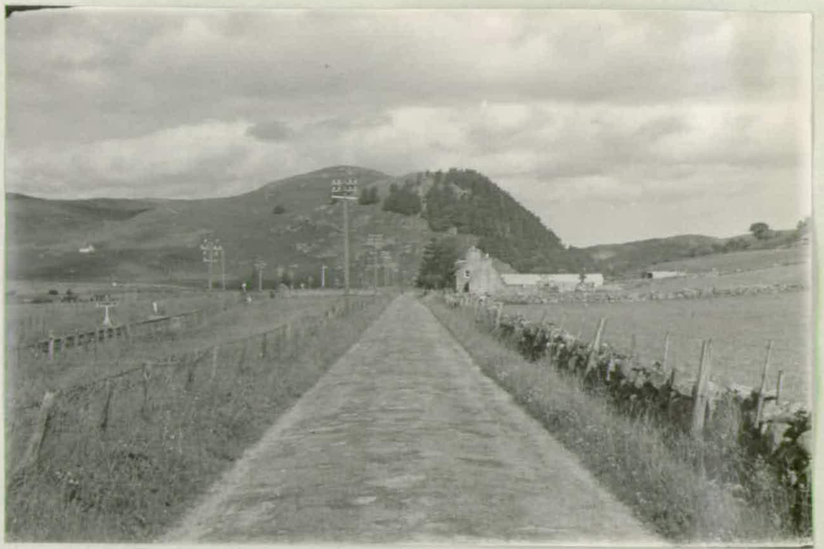

Fig. 67.

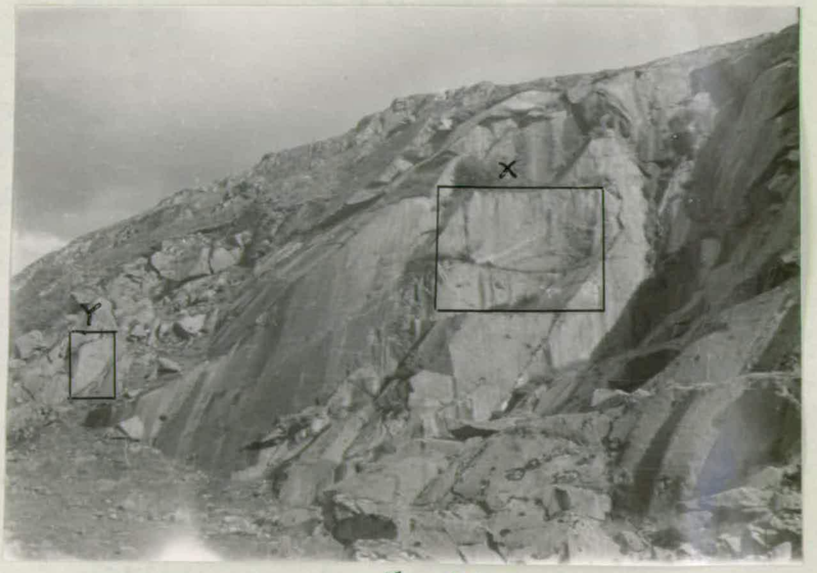

Fig. 68.

Fig. 69.

Eleeation of part of the quarried granodiorite exposures at Dalmore, showing the abundance of inclusions in the granodiorite. The majority of these inclusions are pre-existing pelitic and semi-pelitic Moine schists. The white lines running across the rock surface are aplitic or pegmatitic veins.

Fig. 70.

Elevation of part of the quarried granodiorite exposures at Dalmore, showing the parallel arrangement of the inclusions in the granodiorite. The lie of these inclusions is in agreement with planar foliation of the granodiorite.

Fig. 69.

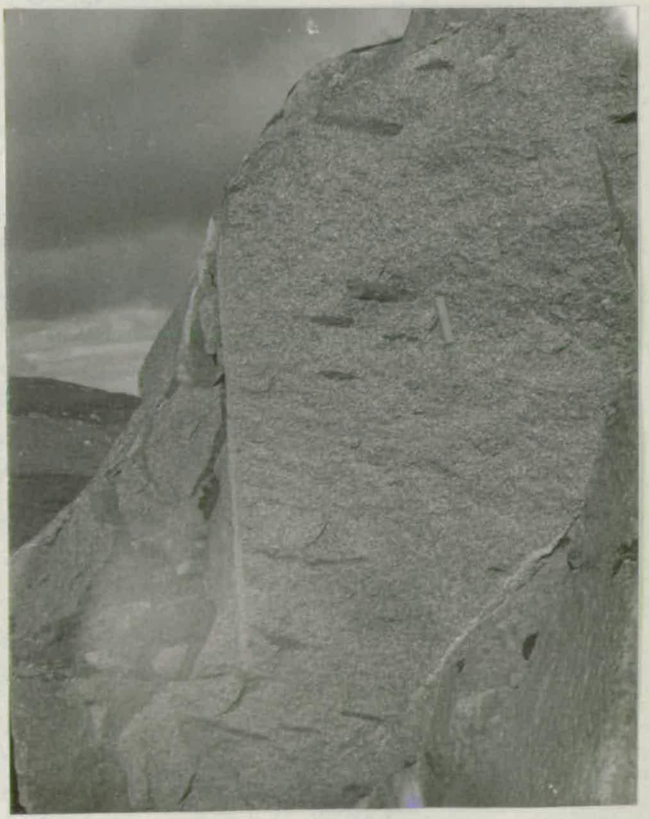

Fig. 70.

Fig. 71.

A sketch of the same exposure shown in Fig. 69, showing the exact position of the inclusions in the granodiorite. Note some of the inclusions are bounded by biotite-rich rims, shown by dashed lines around the margins of the inclusions.

Fig. 72.

A sketch of the rock face shown in Fig. 70, showing the parallel arrangement of the inclusions. Heavy dashed lines show planar foliation of the granodiorite.

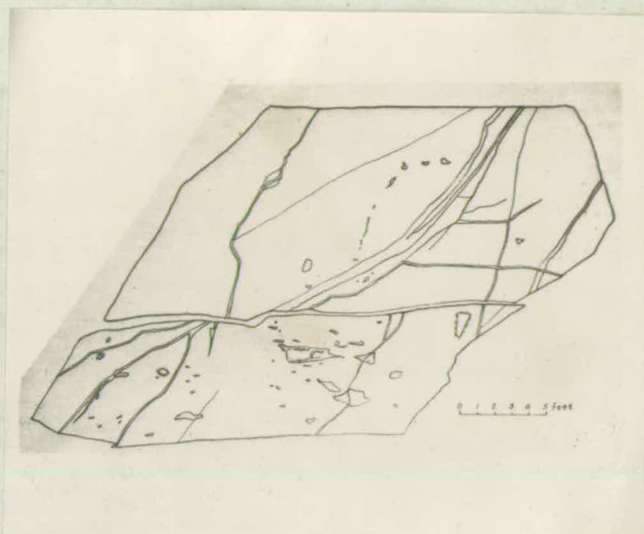

Fig. 71.

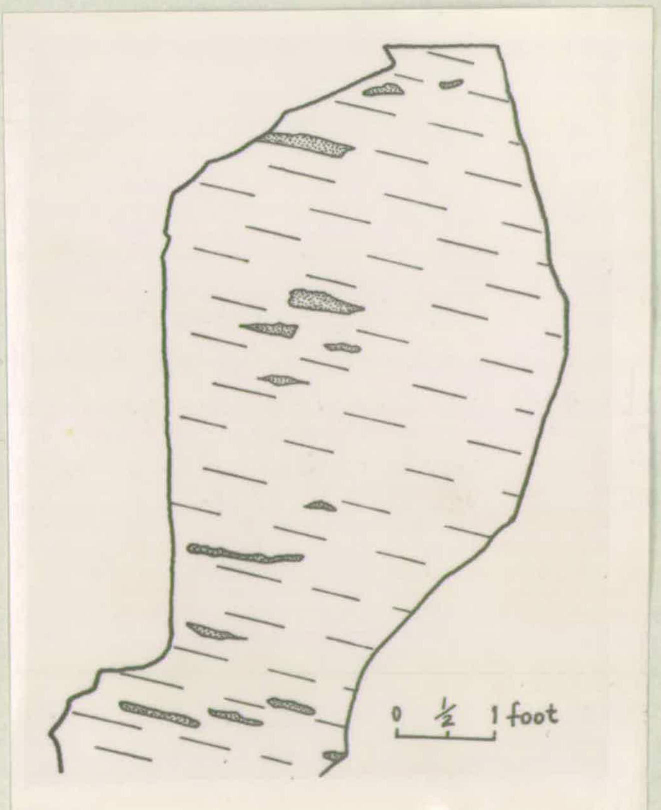

Fig. 72.

Fig. 73.

Photograph of a specimen from Dalmore Granite Quarries, showing inclusions of semi-pelitic schist and siliceous granulite in the granodiorite. The lie of these inclusions is in agreement with the planar foliation of the granodiorite. Note the darker rim enriched in biotite flakes developed from the semi-pelitic schist inclusions at their margins against the granodiorite.

Fig. 74.

A strongly altered inclusion in the granodiorite at Dalmore Quarries, Rogart. Note the complicated network of granitic material in the inclusion.

Fig. 73.

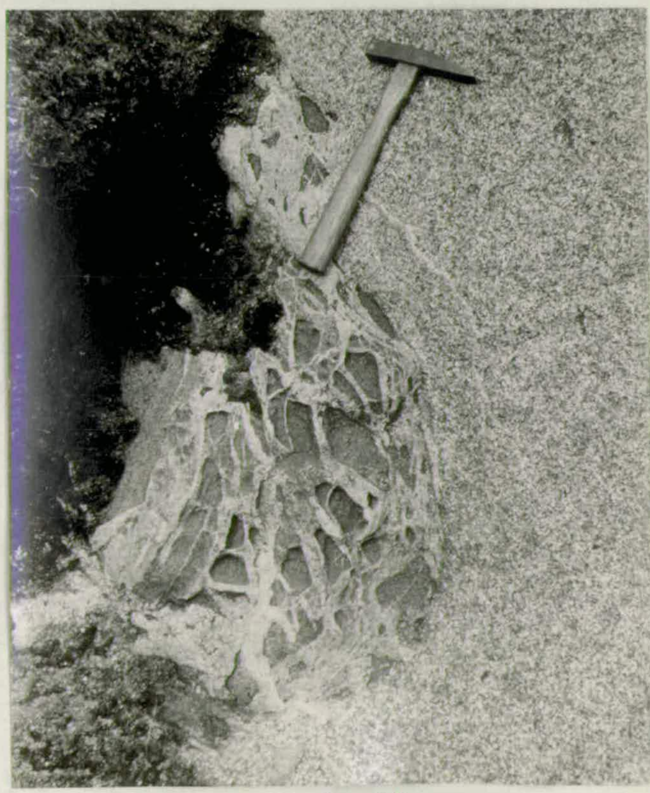

Fig. 74.

Fig. 75.

Aplite veins in the granodiorite on the summit of Creag na Dalach Moire. The aplite veins seem roughly to follow the joint system in the granodiorite.

Fig. 76.

Part of the aplite vein shown in Fig. 75, Creag na Dalach Moire, Rogart.

Fig. 75.

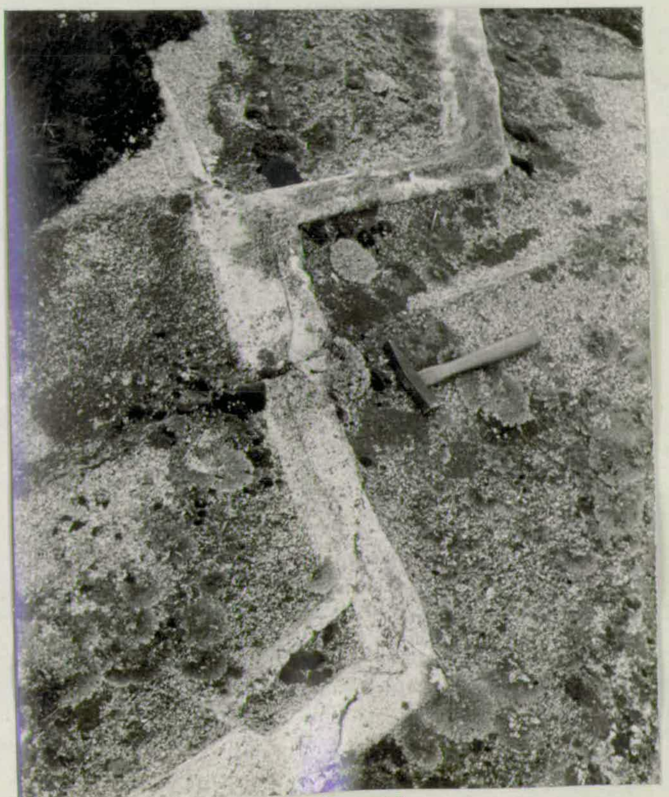

Fig. 76.

Fig. 77.

Valley of Strath Fleet, looking east to the North Sea. The hills on the left-hand side of the picture illustrate the topography typical of the migmatites in the Rogart area. x indicates the position of Rogart Station.

Fig. 78.

Creag Bail' a' Chlaiginn from the south. The houses at the foot of the hill in front are the School of Rogart. The picture shows the surface forms of the migmatites in the Rogart area.

Fig. 77.

Fig. 78.

Fig. 79.

West side of Øreag na Croiche, where the arbitrary boundary between the zone of migmatite and the granodiorite has been drawn.

Fig. 80.

Striped migmatite with relict ghosts in the form of biotite streaks of semi-pelitic schist and siliceous granulite. These biotite-rich films and streaks in the migmatites have the same strike and dip as the Moine rocks outside the zone of migmatites. At the foot of Creag na Croiche, beside the road leading from Little Rogart to Pitfure Lodge.

Fig. 79.

Fig. 80.

Figs. 81 and 82.

Striped migmatites at the summit of Creag a' Bhata, Rogart. The migmatites have a very marked lineation controlled by biotite, combined with a layering in which biotite is less or more common in alternate layers, which weather differentially. These biotite-streakings are regular and persistent over large areas and they agree in strike and dip with the Moine rocks outside the zone of migmatites. The conclusion appears warranted that the structures in the migmatites are relic structures persisting from the pre-existing Moine rocks.

Fig. 81.

Fig. 82.

Fig. 83.

Striped migmatites with relics of semi-pelitic schists. The dip and strike of the foliation of the schist fragments are in agreement with those of the biotite-streakings in the migmatites. The conclusion appears warranted that these biotite streakings are relics from the pre-existing semi-pelitic schists. Creag a' Bhata, Rogart.

Fig. 84.

An enlarged portion of the migmatites shown in Fig. 83 , showing the fine biotite films in the migmatites and their continuity with the foliation of the schist relics. Creag a' Bhata, Rogart.

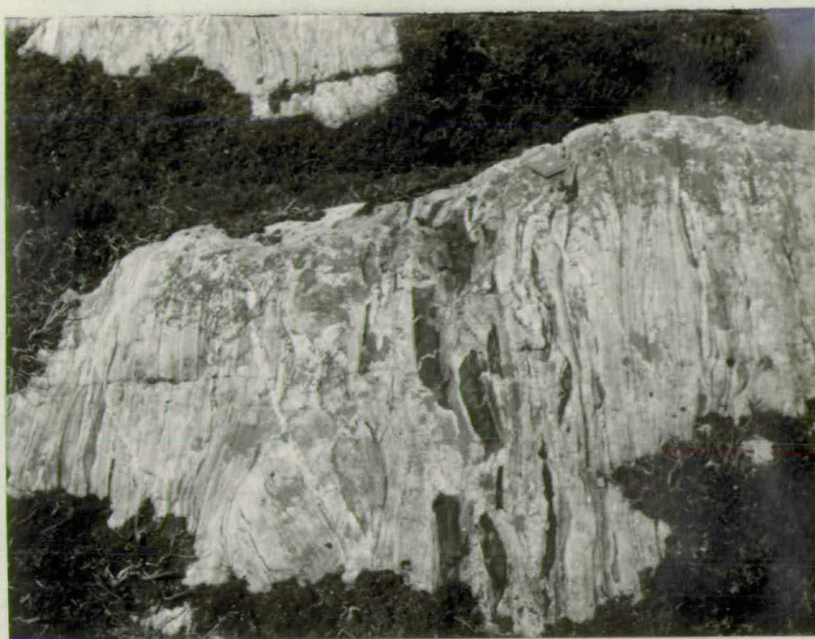

Fig. 83.

Fig. 84.

Fig. 85.

Striped migmatites with relics of semi-pelitic schists, the foliation of the schist being accordant with the layerings of the migmatites. The migmatites show occasional pinkish porphyroblasts of orthoclase. Creag a' Bhata, Rogart.

Fig. 86.

Horizontal surface of migmatites at Creag a' Bhata, with depressed portions occupied by striped migmatites and relict bands of siliceous granulites standing out in relief.

Fig. 85.

Fig. 86.

Fig. 87.

Striped migmatites alternating with siliceous granulites and cut by a pegmatite vein. The siliceous granulites are partly migmatised and show a coarser grain than similar rocks outside the zone of migmatites. Creag a' Bhata, Rogart.

Fig. 88.

Weathered surface of migmatites, with depressed portions occupied by striped migmatites (biotite-granite). The relict siliceous granulites stand out in relief. Note the concordant relationship between these two rock members. South-east of Creag a' Bhata, at the side of a road which leads from Pittentrail to Little Rogart.

Fig. 87.

Fig. 88.

Fig. 89.

Horizontal rock surface, showing the striped migmatites with inclusions of semi-pelitic schists. Creag a' Bhata, north of Pittentrail, Rogart.

Fig. 90.

Horizontal rock surface showing a small-scale boudinage structure in the striped migmatites. Being less elastic, the fine-grained semi-pelitic schist band cracked into sausage-like fragments, while the neighbouring migmatites shaped themselves plastically around the fragments. Pegmatitic materials appear between the dark fragments and also along their sides. Creag a' Bhata, north of Pittentrail, Rogart.

Fig. 89.

Fig. 90.

Fig. 91.

Elevation of part of the quarried rock exposures in a small quarry on the roadside at Culdrain, two miles north-north-east of Rogart Station, showing folding in the migmatitic gneisses. The gneiss is derived from a band of silimanite-bearing mica-schists, which is exposed along the strike of these gneisses further north, at a point half a mile east of Achnagarron.

Fig. 92.

Folded migmatitic gneiss, showing the development of a patch of gneissic granite (lower left-hand corner of the picture) in the migmatitic gneiss. Road-side quarry at Culdrain, Rogart.

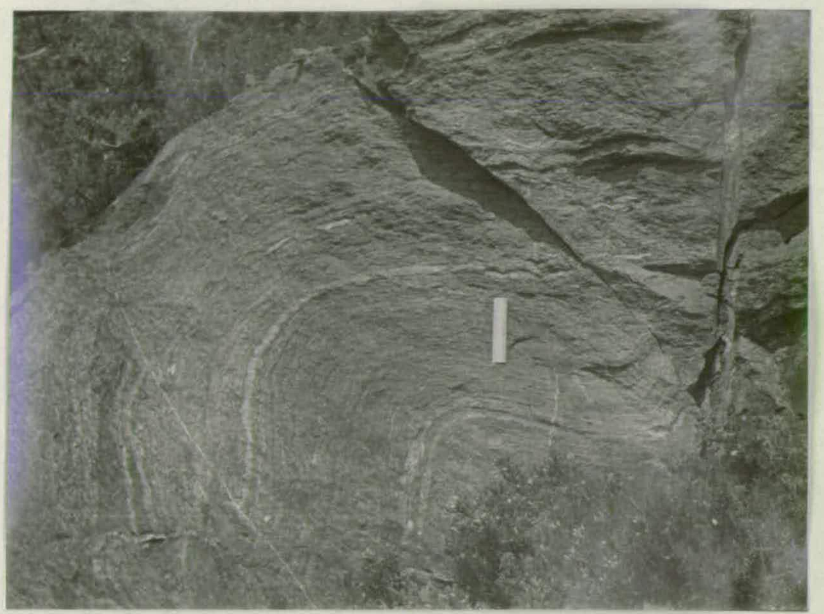

Fig. 91.

Fig. 92.

Fig. 93.

Folded migmatitic gneiss in the road-side quarry at Culdrain, showing minor foldings in the gneisses.

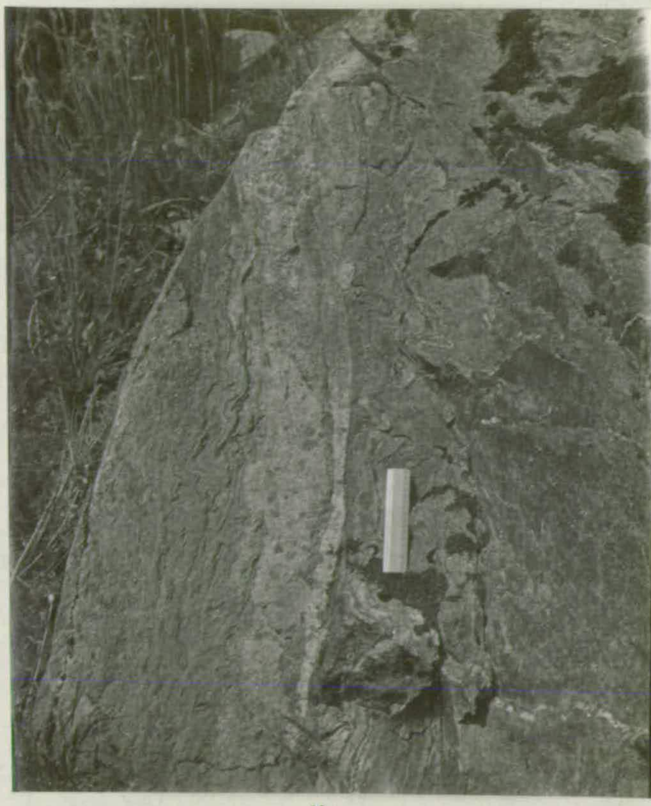

Fig. 93.

Fig. 94.

The northernmost portion of the rock slab shown in Text-Fig. 1, p. 149, showing relict fragments of biotite-hornblende-schist in the granodiorite. 225 yds. N.N.E. of Millnafua Bridge, Rogart.

Fig. 95.

A general view of the rock slab shown in Text-fig. 1, p. 149.

Fig. 94.

Fig. 95.

Fig. 96.

A small rock slab beside the large rock slab shown in Text-fig. 1, p. 149, showing the intricate pattern of the granitic portions which have resulted from the migmatisation of the massive fine-grained biotite-hornblende-schist. With increasing migmatisation and granitisation the granitic portions become increasingly wider until finally the rock-mass as a whole assumes the form of agmatite.

Fig. 96.